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TRAINING-INDUCED COGNITIVE AND NEURAL PLASTICITY

Topic Editors
Julia Karbach and Torsten Schubert

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TRAINING-INDUCED COGNITIVE AND NEURAL PLASTICITY

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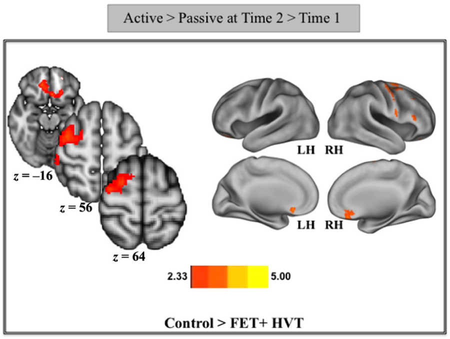

Cortical areas recruited by the controls relative to the two training groups at post-training, when compared to pre-training. Figure taken from Prakash RS, De Leon AA, Mourany L, Lee H, Voss MW, Boot WR, Basak C, Fabiani M, Gratton G and Kramer AF (2012) Examining neural correlates of skill acquisition in a complex videogame training program. *Front. Hum. Neurosci.* 6:115. doi: 10.3389/fnhum.2012.00115

Throughout the entire lifespan, individuals are required to adapt to the demands of changing developmental contexts and dynamic social environments. The potential modifiability of a person's cognitive and neural processes has been referred to as plasticity. One way to assess cognitive and neural plasticity is to apply training interventions and to measure the related changes in trained and untrained situations. Over the last decade, the literature on the effects of cognitive interventions has been growing rapidly, oftentimes focusing on the magnitude, scope, and maintenance of training-related benefits and their transferability to untrained tasks and abilities. Recent studies show that plasticity is present across the lifespan, although it seems to decline in older age, and that the long-term maintenance as well as the transferability of training gains strongly depends on the type and the intensity of the intervention. The findings from behavioral cognitive training research have also been accompanied by findings from cognitive neuroscience. The related observations oftentimes point to training-induced changes in a number of cortical and subcortical regions, which may be responsible for the magnitude of training and of transfer effects. Thus, cognitive training may be a promising tool for understanding basic mechanisms of adaptive behavior on the one hand and for designing applications and interventions within different disciplines in psychology on the other hand. However, not all studies have consistently shown beneficial effects of cognitive training and some questions that are critical for our understanding of plasticity are still unanswered. What are the key processes mediating training effects on laboratory tasks and in real world situations? Which characteristics of the training process and of the trainings situations mediate transfer effects? Are training effects subject to age-related changes? How are training-induced neural changes in the brain related to improvements in cognitive performance? How effective are training interventions in patients with specific cognitive impairments? To what extent can age-related cognitive decline be compensated by means of cognitive training?

The focus of this Research Topic is on training-induced cognitive and neural plasticity across the lifespan. The goal is to provide a broad scope of state-of-the art research in order to enhance our knowledge regarding the mechanisms underlying plasticity. We invite contributions applying behavioral, computational, and neuroscientific approaches, reviews, and theoretical contributions. Contributions are also welcomed if they focus on the implications of cognitive training in applied fields like educational and clinical settings as well as rehabilitation and training science.

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EDITORIAL
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Training-induced cognitive and neural plasticity

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Research on cognitive interventions and training-induced changes in brain and behavior has been of growing interest in cognitive neuroscience and related disciplines over the last decade (for reviews see Hertzog et al., 2008; Lustig et al., 2009; Shipstead et al., 2010; Morrison and Chein, 2011; for a recent meta-analysis see Melby-Lervåg and Hulme, 2013). The aim of this research topic is to provide a broad scope of state-of-the art research in order to advance the understanding of the scope and the mechanisms involved in cognitive and neural plasticity, that is, the potential modifiability of a person's cognitive abilities and brain activity.

Previous studies focusing on the magnitude and maintenance of training-related benefits have indicated that plasticity is considerable in healthy individuals across lifespan (e.g., Brehmer et al., 2007; Karbach and Kray, 2009; Karbach et al., 2010; Dorbath et al., 2011; Strobach et al., 2012a,c), and that it may even extend to very old age (Verhaeghen et al., 1992; Buschkuehl et al., 2008; Zinke et al., 2012b). Aside from training-related improvements on the trained task, researchers are especially interested in understanding the transferability of training-related performance gains to tasks that have not been part of the training. This issue is of particular importance for the application of training programs, e.g., in clinical and educational contexts, but also for the theoretical understanding of the processes underlying training and transfer effects. Recent evidence indicated that transfer effects might be enhanced if the training regime taps higher-level executive control processes instead of focusing on basic processing commodities or specific strategies (Lustig et al., 2009; Noack et al., 2009). Others showed that transfer of training can only occur if the training task and the transfer task engage overlapping cognitive processing components and brain regions (Dahlin et al., 2008). In addition, findings from behavioral cognitive training research have been accompanied by findings from cognitive neuroscience, indicating that cognitive training often induces practice-related changes in the neural substrate (for reviews see; Kelly and Garavan, 2005; Jones et al., 2006; Klingberg, 2010). These observations point to training-induced plasticity in several cortical and subcortical regions which can relate to neural changes within these regions as well as in networks of regions, emphasizing the importance of interdisciplinary approaches for investigating cognitive and neural changes after training.

The contributions of this research topic have addressed the nature, the scope and the preconditions of cognitive and neural plasticity from different angles. Two review articles provide an overview of recent findings on cognitive training in the areas of developmental psychology (Jolles and Crone, 2012) and cognitive aging (Buitenweg et al., 2012). Cognitive plasticity in childhood and in older age has also been addressed by several original research articles (Brehmer et al., 2012; Garrett et al., 2012; Hanna-Pladdy and Gajewski, 2012; Kray et al., 2012; Lövdén et al., 2012; Lussier et al., 2012; Söderqvist et al., 2012; Strobach et al., 2012b; Zinke et al., 2012a). The findings reported in these publications provide strong evidence for the view that cognitive plasticity extends from childhood to older age (c.f. Brehmer et al., 2007; Karbach and Kray, 2009). Moreover, these results are supported by evidence indicting that cognitive plasticity is not only present in healthy individuals, but can also be found in patients suffering from developmental disorders (Kray et al., 2012), intellectual disability (Söderqvist et al., 2012), and chronic traumatic brain injury (Sacco et al., 2011).

In addition to investigating the effectiveness of cognitive training in different populations, such as different age groups or different types of patients, several contributions have also provided evidence for the usefulness of different training regimes. Most of these studies applied process-based training interventions, such as executive-control training (Kray et al., 2012; Lussier et al., 2012; Strobach et al., 2012b), working-memory training (Brehmer et al., 2012; Salminen et al., 2012; Schneiders et al., 2012; Söderqvist et al., 2012) or game training (Prakash et al., 2012; van Muijden et al., 2012), but also different types of physical training (Gajewski and Falkenstein, 2012; Zinke et al., 2012a,b). Nevertheless, it remains open which of these kinds of training most efficiently support the occurrence of transfer effects. Consistent with the growing interest in understanding the neural mechanisms underlying training-induced performance changes, a few of the studies have also applied neurophysiological (Gajewski and Falkenstein, 2012) und neuroimaging techniques (Sacco et al., 2011; Prakash et al., 2012; Schneiders et al., 2012), suggesting that training-induced behavioral changes were accompanied by significant changes in neural activity that varied as a function of the specific training intervention.

Recently, it has also been suggested to analyze training data from an individual differences perspective (see also Garrett et al., 2012). Addressing the question why some individuals benefit more than others from cognitive interventions is particularly important for the adaptation of training regimes to populations with specific needs. Two articles (Buitenweg et al., 2012; Jolles and Crone, 2012) have pointed to the importance of this aspect and Lövdén et al. (2012) have reported significant individual differences in memory training and transfer effects across the lifespan. However, a minimum cognitive capacity seems a necessary precondition for the manifestation of training and transfer effects (Söderqvist et al., 2012).

In sum, the current research topic provides a broad overview of new findings and contributes to a deeper understanding of cognitive and neural plasticity. It shows cognitive training to be a promising tool for investigating basic mechanisms of adaptive behavior and neuronal functioning as well as for designing training applications and interventions. The current findings have also pointed to a number of important topics and unsolved issues that will be relevant for forthcoming research: Among them questions regarding methodological approaches in training research, the mechanisms mediating the transfer of training-related benefits, and the usefulness of training for enhancing activities of daily living in different clinical and non-clinical populations.

REFERENCES

Brehmer, Y., Li, S. C., Müller, V., von Oertzen, T., and Lindenberger, U. (2007). Memory plasticity across the life span: uncovering children's latent potential. *Dev. Psychol.* 43, 465–478.

Brehmer, Y., Westerberg, H., and Bäckman, L. (2012). Working-memory training in younger and older adults: training gains, transfer, and maintenance. *Front. Hum. Neurosci*. 6:63. doi: 10.3389/fnhum.2012.00063

Buitenweg, J. I. V., Murre, J. M. J., and Ridderinkhof, K. R. (2012). Brain training in progress: a review of trainability in healthy seniors. *Front. Hum. Neurosci*. 6:183. doi: 10.3389/fnhum.2012.00183

Buschkuehl, M., Jaeggi, S. M., Hutchison, S., Perrig-Chiello, P., Däpp, C., Müller, M., et al. (2008). Impact of working memory training on memory performance in old-old adults. *Psychol. Aging* 23, 743–753.

Dahlin, E., Neely, A. S., Larsson, A., Bäckman, L., and Nyberg, L. (2008). Transfer of learning after updating training mediated by the striatum. *Science* 320, 1510–1512.

Dorbath, L., Hasselhorn, M., and Titz, C. (2011). Aging and executive functioning: a training study on focus-switching. *Front. Psychol*. 2:257. doi: 10.3389/fpsyg.2011.00257

Gajewski, P. D., and Falkenstein, M. (2012). Training-induced improvement of response selection and error detection in aging assessed by task switching: effects of cognitive, physical, and relaxation training. *Front. Hum. Neurosci.* 6:130. doi: 10.3389/fnhum.2012.00130

Garrett, D. D., MacDonald, S. W. S., and Craik, F. I. M. (2012). Intraindividual reaction time variability is malleable: feedback- and education-related reductions in variability with age. *Front. Hum. Neurosci.* 6:101. doi: 10.3389/fnhum.2012.00101

Hanna-Pladdy, B., and Gajewski, B. (2012). Recent and past musical activity predicts cognitive aging variability: direct comparison with general lifestyle activities. *Front. Hum. Neurosci*. 6:198. doi: 10.3389/fnhum.2012.00198

Hertzog, C., Kramer, A. F., Wilson, R. S., and Lindenberger, U. (2008). Enrichment effects on adult cognitive development. *Psychol. Sci. Public Interest* 9, 1–65.

Jolles, D. D., and Crone, E. A. (2012). Training the developing brain: a neurocognitive perspective. *Front. Hum. Neurosci.* 6:76. doi: 10.3389/fnhum.2012.00076

Jones, S., Nyberg, L., Sandblom, J., Stigsdotter Neely, A., Ingvar, M., Petersson, K. M., et al. (2006). Cognitive and neural plasticity in aging: general and task-specific limitations. *Neurosci. Behav. Rev.* 30, 846–871.

Karbach, J., and Kray, J. (2009). How useful is executive control training? Age differences in near and far transfer of task-switching training. *Dev. Sci.* 12, 978–990.

Karbach, J., Mang, S., and Kray, J. (2010). Transfer of task-switching training in older age: the role of verbal processes. *Psychol. Aging* 25, 677–683.

Kelly, A. M. C., and Garavan, H. (2005). Human functional neuroimaging of brain changes associated with practice. *Cereb. Cortex* 15, 1089–1102.

Klingberg, T. (2010). Training and plasticity of working memory. *Trends Cogn. Sci.* 14, 317–324.

Kray, J., Karbach, J., Haenig, S., and Freitag, C. (2012). Can task- switching training enhance executive control functioning in children with attention deficit/-hyperactivity disorder? *Front. Hum. Neurosci.* 5:180. doi: 10.3389/fnhum.2011.00180

Lövdén, M., Brehmer, Y., Li, S.-C., and Lindenberger, U. (2012). Training-induced compensation versus magnification of individual differences in memory performance. *Front. Hum. Neurosci.* 6:141. doi: 10.3389/fnhum.2012.00141

Lussier, M., Gagnon, C., and Bherer, L. (2012). An investigation of response and stimulus modality transfer effects after dual-task training in younger and older. *Front. Hum. Neurosci.* 6:29. doi: 10.3389/fnhum.2012.00129

Lustig, C., Shah, P., Seidler, R., and Reuter-Lorenz, P. A. (2009). Aging, training, and the brain: a review and future directions. *Neuropsychol. Rev.* 19, 504–522.

Melby-Lervåg, M., and Hulme, C. (2013). Is working memory training effective? A meta-analytic review. *Dev. Psychol*. 49, 270–291.

Morrison, A. B., and Chein, J. M. (2011). Does working memory training work? The promise and challenges of enhancing cognition by training working memory. *Psychon. Bull. Rev.* 18, 46–60.

Noack, H., Lövdén, M., Schmiedek, F., and Lindenberger, U. (2009). Cognitive plasticity in adulthood and old age: gauging the generality of cognitive intervention effects. *Restor. Neurol. Neurosci*. 27, 435–453.

Prakash, R. S., De Leon, A. A., Mourany, L., Lee, H., Voss, M. W., Boot, W. R., et al. (2012). Examining neural correlates of skill acquisition in a complex videogame training program. *Front. Hum. Neurosci.* 6:115. doi: 10.3389/fnhum.2012.00115

Sacco, K., Cauda, F., D'Agata, F., Duca, S., Zettin, M., Virgilio, R., et al. (2011). A combined robotic and cognitive training for locomotor rehabilitation: evidences of cerebral functional reorganization in two chronic traumatic brain injured patients. *Front. Hum. Neurosci.* 5:146. doi: 10.3389/fnhum.2011.00146

Salminen, T., Strobach, T., and Schubert, T. (2012). On the impacts of working memory training on executive functioning. *Front. Hum. Neurosci.* 6:166. doi: 10.3389/fnhum.2012.00166

Schneiders, J. A., Opitz, B., Tang, H., Deng, Y. A., Xie, C., Li, H., et al. (2012). The impact of auditory working memory training on the fronto-parietal working memory network. *Front. Hum. Neurosci.* 6:173. doi: 10.3389/fnhum.2012.00173

Shipstead, Z., Redick, T. S., and Engle, R. W. (2010). Does working memory training generalize? *Psychol. Belgica* 50, 245–276.

Söderqvist, S., Nutley, S. B., Ottersen, J., Grill, K. M., and Klingberg, T. (2012). Computerized training of non-verbal reasoning and working memory in children with intellectual disability. *Front. Hum. Neurosci.* 6:271. doi: 10.3389/fnhum.2012.00271

Strobach, T., Frensch, P. A., Müller, H. J., and Schubert, T. (2012a). Age- and practice-related influences on dual- task costs and compensation mechanisms under optimal conditions for dual-task performance. *Aging Neuropsychol. Cogn.* 19, 222–247.

Strobach, T., Frensch, P., Müller, H. J., and Schubert, T. (2012b) Testing the limits of optimizing dual- task performance in younger and older adults. *Front. Hum. Neurosci.* 6:39. doi: 10.3389/fnhum.2012.00039

Strobach, T., Liepelt, R., Schubert, T., and Kiesel, A. (2012c). Task switching: effects of practice on switch and mixing costs. *Psychol. Res.* 76, 74–83.

van Muijden, J., Band, G. P. H., and Hommel, B. (2012). Online games training aging brains: limited transfer to cognitive control functions. *Front. Hum. Neurosci.* 6:221. doi: 10.3389/fnhum.2012.00221

Verhaeghen, P., Marcoen, A., and Goossens, L. (1992). Improving memory performance in the aged through mnemonic training: a meta-analytic study. *Psychol. Aging* 7, 242–251.

Zinke, K., Einert, M., Pfennig, L., and Kliegel, M. (2012a). Plasticity of executive control through task switching training in adolescents. *Front. Hum. Neurosci.* 6:41. doi: 10.3389/fnhum.2012.00041

Zinke, K., Zeintl, M., Eschen, A., Herzog, C andKliegel, M. (2012b). Potentials and limits of plasticity induced by working memory training in old-old age. *Gerontology* 58, 79–87.

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Recent and past musical activity predicts cognitive aging variability: direct comparison with general lifestyle activities

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Studies evaluating the impact of modifiable lifestyle factors on cognition offer potential insights into sources of cognitive aging variability. Recently, we reported an association between extent of musical instrumental practice throughout the life span (greater than 10 years) on preserved cognitive functioning in advanced age. These findings raise the question of whether there are training-induced brain changes in musicians that can transfer to non-musical cognitive abilities to allow for compensation of age-related cognitive declines. However, because of the relationship between engagement in general lifestyle activities and preserved cognition, it remains unclear whether these findings are specifically driven by musical training or the types of individuals likely to engage in greater activities in general. The current study controlled for general activity level in evaluating cognition between musicians and nomusicians. Also, the timing of engagement (age of acquisition, past versus recent) was assessed in predictive models of successful cognitive aging. Seventy age and education matched older musicians (>10 years) and non-musicians (ages 59–80) were evaluated on neuropsychological tests and general lifestyle activities. Musicians scored higher on tests of phonemic fluency, verbal working memory, verbal immediate recall, visuospatial judgment, and motor dexterity, but did not differ in other general leisure activities. Partition analyses were conducted on significant cognitive measures to determine aspects of musical training predictive of enhanced cognition. The first partition analysis revealed education best predicted visuospatial functions in musicians, followed by recent musical engagement which offset low education. In the second partition analysis, early age of musical acquisition (<9 years) predicted enhanced verbal working memory in musicians, while analyses for other measures were not predictive. Recent and past musical activity, but not general lifestyle activities, predicted variability across both verbal and visuospatial domains in aging. These findings are suggestive of different use-dependent adaptation periods depending on cognitive domain. Furthermore, they imply that early age of musical acquisition, sustained and maintained during advanced age, may enhance cognitive functions and buffer age and education influences.

Keywords: music, cognitive aging, modifiable factors of aging, lifestyle activities, training-induced changes

INTRODUCTION

Cognitive aging variation is evident from studies documenting numerous individual characteristics associated with enhanced cognitive functioning in advanced age (Kramer et al., 2004). Age-related cognitive declines have consistently been documented primarily in reduced processing capacity and fluid abilities with acceleration in the fifth and sixth decades (Salthouse, 2004). Despite these declines, evidence suggests that measures of knowledge remain stable or improve with age and that there may be large individual variability in terms of successful cognitive aging (Anstey and Smith, 1999; Kramer et al., 2004). Thus, age-associated cognitive declines may not be inevitable, with increasing evidence that several factors and/or lifestyle activities may predict the course of cognitive development across the life span. Lifestyle factors are gaining support as modifiable variables in aging that may delay the expression of brain pathology theoretically because of greater ability to compensate for deficits through alternate neural mechanisms reflective of functional reserve (Cabeza et al., 2002; Scarmeas et al., 2003; Hall et al., 2009; Stern and Munn, 2010). Many positive environmental influences on cognition and brain plasticity during aging have been considered including physical and leisure activities, educational and occupational activities, bilingualism, and high levels of experience and expertise in either occupational or leisure pursuits (Kramer et al., 2004; Springer et al., 2005; Valenzuela and Sachdev, 2006; Bialystok et al., 2007; Craik et al., 2010). While maintaining cognitive vitality is critical for enhanced quality of life in advanced age, few human studies have systematically evaluated cognitive enrichment with most studies focusing on physical and leisure activities (Scarmeas et al., 2003; Verghese et al., 2003; Wilson et al., 2003). Animal and human data suggest that lifelong learning may contribute to cognitive vitality late in life by increasing synaptic complexity and neurogenesis, and that staying engaged in intellectually stimulating activities may protect and maintain cognitive and brain function (Greenough et al., 1986; Fillit et al., 2002; Kramer et al., 2004; Newson and Kemps, 2005; Green and Bavelier, 2008). Cognitively stimulating activities such as playing bridge, completing cross word puzzles, and high educational and occupational attainment are associated with better cognitive functioning in advanced age, but it is difficult to determine whether these are related to the cognitive aspects of activity-induced learning or related to the types of individuals likely to engage in greater activities either throughout their life or in advanced age (Kramer et al., 2004; Newson and Kemps, 2005). Also, quantification of cognitively stimulating activities across the life span is impractical given that individuals would be required to retrospectively estimate the number of hours spent reading, playing games, or completing cross word puzzles, making it difficult to discern the critical timing of engagement and durations needed for optimal outcomes.

Although most learning paradigms employed in the laboratory designed to facilitate cognitive enhancement are specific and poorly generalize to other tasks, several lines of recent evidence offer hope for transfer effects with more extensive training (Jaeggi et al., 2008; Karbach and Kray, 2009). Also, complex real life activities involving skilled movements such as musical training, video games, golf and juggling are more likely to yield general learning effects (Boyke et al., 2008; Forgeard et al., 2008; Green and Bavelier, 2008; Bezzola et al., 2011, 2012). Instrumental musical activities are cognitively and motorically complex, tapping into many systems in parallel (auditory, sensorimotor, visuospatial, memory, processing speed, working memory), and require intensive repetitive practice over many years that is likely to yield differential brain organization that has the potential to yield more robust transfer across tasks related to enhanced brain plasticity (Elbert et al., 1995; Gaser and Schlaug, 2003; Koelsch et al., 2005; Bangert et al., 2006; Fujioka et al., 2006; Green and Bavelier, 2008; Jancke, 2009a,b; Moreno et al., 2011a). Also, musical training can be readily quantified across the life span in terms of the number of years of practice, age of acquisition, and formal years of training, and therefore, may serve as an ideal model for quantifying the effects of cognitive stimulation throughout the life span on successful aging. There is a growing body of literature supporting the influence of musical training early in development in shaping non-musical cognitive and motor functions (Costa-Giomi et al., 2001; Ho et al., 2003; Schellenberg, 2004; Koelsch et al., 2005; Penhune et al., 2005; Schlaug et al., 2005; Fujioka et al., 2006; Moreno et al., 2011a). The strongest evidence of musical transfer to non-musical cognitive functions is derived from studies exploring the effect of musical training on speech and language (Loui et al., 2011; Ott et al., 2011; Patel, 2011; Shahin, 2011). However, with the focus on music education and development, few studies have evaluated how participation in musical activities may enhance cognition in advanced age.

In a recent study, we demonstrated that instrumental musicians with extended practice across the life span displayed better cognition in advanced age (60–83 years of age). Specifically, at least 10 years of musical participation across the life span had a strong predictive effect on preserved cognitive functioning across both verbal and visuospatial domains, and for executive processes (Hanna-Pladdy and Mackay, 2011). These cognitive advantages persisted even when the musicians were not active in advanced age, and were not accounted for on the basis of intelligence or education. This suggests that musical training may prove to be a modifiable factor that can enhance successful cognitive aging by increasing neuroplasticity, and is consistent with the range of cognitive advantages following musical training in children (Pantev et al., 2003; Forgeard et al., 2008; Moreno et al., 2011b). This is supported by a recent study that reported less age-related decline in central auditory processing for lifelong musicians (Zendel and Alain, 2012). While another study also identified auditory enhancements in instrumental musicians with extensive practice into middle adulthood (45–65 years of age), this study failed to reveal differences for visuospatial functions (Parbery-Clark et al., 2011). Moreover, this study did not replicate the association between extent of musical training or find significant contributions from age of acquisition, although methodological limitations such as verbal intelligence differences and inclusion of individuals with musical training in the non-musician group, may have obscured interpretation of the findings (Parbery-Clark et al., 2011). Previous work in middle-aged professional musicians revealed increased gray matter density in Broca's area correlating with enhanced visuospatial functions suggesting that musicians may uniquely utilize a left lateralized network for visuospatial processing (Sluming et al., 2002, 2007). Furthermore, age-related volume reductions in frontal regions have demonstrated attenuation in atrophy for middle-aged professional musicians (Sluming et al., 2002). Therefore, based on recent findings, there is strong evidence supporting brain plasticity in lifelong musicians with potential transfer to non-musical cognitive functions.

Nonetheless, several questions remain including whether cognitive advantages in musicians are related to training effects or a selection factor of who engages in musical activity (i.e., more intelligent or more active individuals), and whether transfer to functions outside of the auditory/verbal domain is possible (Schellenberg and Peretz, 2008). Also, while we accounted for physical exercise in our first investigation, we did not account for general lifestyle activities making it unclear if increased general activity level in musicians may have accounted for differences between the groups instead of musical training (Stern and Munn, 2010). This is a plausible hypothesis given that general lifestyle activities have reliably predicted cognitive change in older adults (Newson and Kemps, 2005). Consequently, this warrants further investigation in particular related to whether musical training may buffer age-related cognitive declines in older individuals at the age of greatest risk for development of a neurodegenerative process (i.e., over the age of 60). In the current study, we selected a sample of subjects comparable to our first study to further ascertain whether general activity level between musicians and non-musicians might account for differences in cognitive outcomes. Based on our previous results, we only selected musicians with greater than 10 years of musical experience, since musicians with 1–9 years of training were not previously different from non-musicians (Hanna-Pladdy and Mackay, 2011). Second, we evaluated predictive models to try and identify whether there are critical aspects of musical experience such as timing of engagement (i.e., age of acquisition or continued activity in advanced age) that may predict cognitive aging variability. Although age of acquisition has been demonstrated as critical in acquiring language, few studies have directly compared the effects of past and more recent experience in determining how the timing of stimulation influences cognitive development across the life span. While some cognitive capacities such as language and related auditory/verbal functions may have early critical sensitive periods, other functions may be more amenable to cognitive stimulation later in life, informing us of the potential differences in plasticity that may be harnessed and guiding future models of cognitive stimulation.

MATERIALS AND METHODS

SUBJECTS

Seventy community-dwelling older adults between 59 and 80 years of age were selected for this study which was conducted at the Kansas University School of Medicine (KUMC). The following two groups of individuals were selected for the present study on the basis of their previous experience with instrumental musical participation across the lifespan: (1) *Non-musicians* ($n = 37$) – less than 1 year of musical participation, and (2) *Musicians* ($n = 33$) – more than 10 years of instrumental musical participation. Inclusion of musicians with greater than 10 years of experience was based on results from our previous study which demonstrated statistically significant cognitive differences between musicians with 10 or more years of experience relative to non-musicians, but no differences for musicians with 1–9 years of experience. In the current study, we selected an independent sample of subjects, but with similar characteristics to the previous study. The musician and non-musician groups were matched on age and education, were native English speakers and strongly right hand dominant as determined by the Edinburgh Handedness Inventory (at least +60 on the inventory; see **Table 1**; Oldfield, 1971). Subjects were non-demented based on neuropsychological and functional data (Adelaide Activities Profile) and did not endorse significant history of psychiatric, substance abuse, or chronic medical illness (Folstein et al., 1975; Clark and Bond, 1995; see **Table 1**). This study was approved by the KUMC institutional review board and written informed consent was obtained from all participants.

CHARACTERISTICS OF MUSICIANS

The authors conducted a structured interview which was administered by the experimenter to obtain information regarding musical experience. The subjects were required to describe all musical experiences, age of acquisition, training settings, and exposure to various musical instruments and practice routines across their life span. Musicians selected for inclusion in the study were required to have a minimum of 10 years of musical activity with at least one musical instrument at any time in their life span. The majority of the musicians exceeded the minimum 10-year requirement (mean of 37 years), and 50% had experience with multiple instruments. The mean age of acquisition was 9.3 years of age, with a mean 4 years of formal musical training. Musicians were not required to be actively engaged in musical activities at the time of the evaluation, although close to half the group continued to actively participate in music with some regularity in advanced age. Piano was the most common instrument (61.8%), followed by strings (17.6%), horns (14.7%), woodwinds (2.9%) and percussion (2.9%). The characteristics of the musicians in the current study are similar to our previous study, with the exception that a greater proportion of high activity musicians (>10 years) in the current study had experience with multiple instruments (Hanna-Pladdy and Mackay, 2011).

LEVEL OF GENERAL ACTIVITY

We used the Adelaide Activities Profile (AAP) as a measure of general activity level (Clark and Bond, 1995). The AAP was developed from the Frenchay Activities Index, and is a validated measure of lifestyle activities in the elderly (Clark and Bond, 1995). The AAP provides a profile of the lifestyle activities of older adults by measuring behavior and physical capacity to carry out a number of daily tasks. On this scale, participants are asked to rate 21 items on a four-point Likert scale (scored between 0 and 3) to indicate their frequency of participation over the previous 3 months. Higher scores represent a higher frequency of participation in domestic, health, and social activities. Based on principal component analysis conducted by Clark and Bond, the AAP was grouped into four categories: household maintenance (e.g., gardening, car maintenance), domestic chores (e.g., washing dishes, preparing a meal), social activities (e.g., outdoor recreation or sports, participating in a club), and service to others (e.g., caring for other family members, doing volunteer work).

NEUROPSYCHOLOGICAL ASSESSMENT

All participants received a comprehensive neuropsychological assessment similar to what is typically utilized in a clinical setting for evaluation of age-related cognitive declines. Neuropsychological evaluation is considered the most effective differential diagnostic method in discriminating pathophysiological dementia from age-related cognitive decline, and other related disorders (Grober et al., 1988; Morgan and Baade, 1997). While there are a number of different cognitive screening measures for age-related cognitive decline, they have demonstrated high rates of false negatives, and are not as sensitive. Consequently, full neuropsychological assessments are valuable as sensitive measures and provide more detailed assessment procedures for several cognitive domains, and to be able to discriminate normal aging from beginning dementia (Jacova et al., 2007). Since this study focuses on whether musical training may enhance successful cognitive aging related to neuroplasticity and cognitive reserve, we employed a clinical assessment that is sensitive to evaluation for the risk of the development of dementia (i.e., significant impairment in three cognitive domains with associated functional declines).

Measures from the following cognitive domains were included: memory, attention, language, visuospatial, executive, and sensorimotor functioning. See **Table 1** for the specific measures included in the neuropsychological battery.

The information subtest of the WAIS-III was also administered, and provides a good estimate of general intellectual ability and

Table 1 | Means (SDs) for demographics and scaled scores for neuropsychological measures.

	Non-musicians ($n = 37$)	Musicians ($n = 33$)	F	Sig. ($p < 0.05$)	Effect size
Age	68.81 (5.15)	68.45 (4.45)	0.095	0.759	0.001
Education	16.75 (1.75)	16.94(1.48)	0.219	0.641	0.003
AAP	44.25 (6.48)	45.33 (7.02)	0.445	0.507	0.007
Edinburgh inventory	87.76 (11.91)	91.06 (10.06)	1.55	0.217	0.022
WAIS-III information	12.58 (2.69)	13.21 (2.08)	1.16	0.285	0.017
D-KEFS semantic fluency	12.78 (3.38)	13.94 (3.05)	2.23	0.140	0.032
D-KEFS letter fluency	11.22 (3.15)	13.12 (3.49)	**5.76**	**0.019**	**0.078***
D-KEFS switching fluency	12.46 (2.96)	13.00 (2.39)	0.694	0.408	0.010
Boston naming test	12.22 (2.85)	12.97 (2.36)	1.43	0.236	0.021
WAIS-III digit span	10.73 (2.30)	11.69 (3.07)	2.25	0.139	0.032
WAIS-III LN sequencing	11.37 (2.00)	12.36 (2.16)	**3.91**	**0.05**	**0.054***
WMS-III spatial span	12.4 (3.04)	12.0 (2.69)	0.345	0.559	0.005
D-KEFS trails 1	12.45 (2.02)	12.15 (2.19)	0.373	0.543	0.005
D-KEFS trails 4	12.21 (1.70)	12.61 (1.48)	1.04	0.313	0.015
CVLT-II total (trials 1-4)	0.338 (0.951)	0.409 (0.852)	0.108	0.743	0.002
CVLT-II SDFR	0.203 (1.04)	0.636 (0.730)	**3.99**	**0.05**	**0.055***
CVLT-II LDFR	0.270 (0.93)	0.470 (0.750)	0.957	0.331	0.014
WMS-III visual reproduction I	12.84 (2.78)	12.67 (2.41)	0.075	0.785	0.000
WMS-III visual reproduction II	15.19 (2.22)	14.82 (2.11)	0.509	0.478	0.004
ROCF copy	11.43 (1.44)	11.69 (1.19)	0.691	0.409	0.010
ROCF – immediate recall	11.57 (3.04)	11.52 (2.74)	0.006	0.940	0.000
ROCF – delayed recall	11.68 (2.71)	10.97 (3.04)	1.06	0.307	0.015
Benton JLO	54.24 (5.16)	56.51 (3.54)	**4.51**	**0.037**	**0.062***
Benton visual form discrim.	31 (2.00)	39.97 (1.49)	0.005	0.943	0.000
WCST – perseverations	114.4 (23.5)	110.4 (22.1)	0.507	0.479	0.008
WCST – categories	3.22 (1.49)	3.00 (1.39)	0.390	0.535	0.006
Tower – total	11.92 (2.27)	11.79 (2.55)	0.052	0.820	0.001
Tower – rule violation	10.62 (0.72)	10.91 (0.290)	**4.57**	**0.036**	**0.063***
Grooved pegboard-RH	7.62 (2.25)	8.69 (2.60)	3.43	0.068	0.048
Grooved pegboard-LH	7.41 (2.48)	8.45 (2.29)	3.36	0.071	0.047
Finger tapping-RH	7.86 (3.14)	8.55 (2.93)	0.874	0.353	0.013
Finger tapping-LH	7.67 (3.08)	8.89 (2.92)	2.79	0.100	0.039

AAP, Adelaide activities profile; WAIS-III, Wechsler adult intelligence scale third edition; D-KEFS, Delis–Kaplan executive function system; CVLT-II, California verbal learning test second edition; SDFR, short delay free recall; LDFR, long delay free recall; WMS-III, Wechsler memory scale third edition; VR I, visual reproduction immediate recall; VR II, visual reproduction delayed recall; LNS, letter-number sequencing; JLO, judgment of line orientation; ROCF, Rey Osterrieth Complex Figure; WCST, Wisconsin card sorting task; RH, right hand; LH, left hand. AAP out of maximum 63; WCST Categories out of a maximum 6; JLO out of a maximum of 60 items; CVLT in z score deviations from the mean.

$^*p < 0.05$.

verbal intelligence which is stable with advanced age (Wechsler, 1997a). Verbal memory performance was measured by the California Verbal Learning Test, Second edition (CVLT-II, standard version; Delis et al., 2000), while non-verbal memory was measured by the Wechsler Memory Scale Third Edition (WMS-III) Visual Reproduction I and II subtests (Wechsler, 1997b), and the Rey Osterrieth Complex Figure (ROCF; Rey and Osterrieth, 1939, 1993; Osterrieth, 1944). Verbal attention and working memory were measured by the Digit Span (DS) subtest of the WAIS-III, and the Letter-Number Sequencing (LNS) subtest of the WAIS-III (Wechsler, 1997a). Visual attention, working memory, and visuospatial functioning were measured by the Spatial Span (SS) subtests of the WMS-III (Wechsler, 1997b), Benton Judgment of Line Orientation (JLO), and Benton Visual Form Discrimination (BVFD; Benton et al., 1994). Delis–Kaplan Executive Function System (D-KEFS) Trails 1–5 which also measure cognitive flexibility by asking the subject to switch rapidly between numbers and letters (Delis et al., 2004). Verbal and language functions were measured with the Boston Naming Test (BNT; Kaplan et al., 1983), and D-KEFS letter and phonemic fluency (Delis et al., 2004). Frontal-executive functions were measured by the Wisconsin Card Sorting Test (WCST; Grant and Berg, 1948), and the D-KEFS Tower Test (Delis et al., 2004). The Finger Tapping Test (FT) was used to measure the speed of open loop movements, and required participants to place their hand on a finger tapping board and tap as fast as they could for five 10-s trials (Reitan and Wolfson, 1993). The Grooved Pegboard Test (GP) was used to assess closed loop movements for each hand, and required rotation of small grooved pegs and placement into a board filled with keyhole-shaped holes (Reitan and Wolfson, 1993).

STATISTICAL ANALYSES

Several analyses of variance (ANOVA) were conducted on the neuropsychological measures to determine between-group differences based on musical activity across the lifespan (musicians versus non-musicians). We also fitted several different partition regressions, that partition data according to a non-parametric relationship between the independent variables and the dependent variables by creating a tree (SAS, 2008). A regression tree is a non-parametric model that makes no parametric assumption about the errors. For these reasons, it is not necessary to test parametric fulfillment. The process uses binary partitions. For each level of the tree, it splits into two parts. Regression trees are good for exploring relationships without having a prior model and the results are very interpretable (SAS, 2008). These regression trees estimate optimal cut-points of the independent variables that best predict a dependent variable (categorical or continuous). In order to avoid biased estimates of R square, a fivefold cross validation was reported. The regressions were conducted on the neuropsychological tests revealing between-group differences, to determine the predictors of cognitive performance in musicians.

RESULTS

GROUP DIFFERENCES

Estimate of verbal intellectual ability

An ANOVA evaluating verbal intellectual ability did not reveal between-group differences for the Information subset of the WAIS-III, $F(1, 68) = 1.16$, $p = \text{ns}$ (see **Table 1** for means). Although the estimated verbal intellectual abilities of non-musicians were slightly lower than musicians, this was not statistically significant (**Table 1**).

Attention, working memory, and visuomotor integration

Between-subject effects were significant for verbal working memory as measured by the WAIS-III LNS subtest, $F(1, 68) = 3.91$, $p < 0.05$. Musicians (mean = 12.36) displayed higher scaled scores than non-musicians (mean = 11.37; see **Table 1**). ANOVAs for the Digit Span subtest of the WAIS-III, $F(1, 68) = 2.25$, $p = \text{ns}$, D-KEFS Trails 1, $F(1, 68) = 0.373$, $p = \text{ns}$, D-KEFS Trails 2, $F(1, 68) = 0.003$, $p = \text{ns}$, D-KEFS Trails 3, $F(1, 68) = 0.058$, $p = \text{ns}$, D-KEFS Trails 4, $F(1, 68) = 1.035$, $p = \text{ns}$, and D-KEFS Trails 5, $F(1, 68) = 0.002$, $p = \text{ns}$, were not significant between-groups for either verbal or visual attentional functions.

Language and fluency

D-KEFS letter fluency revealed significant between-group differences consistent with higher scaled scores for musicians (mean = 13.12) relative to non-musicians (mean = 11.22), $F(1, 68) = 5.76$, $p < 0.05$. There were no significant between-group differences for naming on the BNT, $F(1, 68) = 1.43$, $p = \text{ns}$, D-KEFS semantic fluency, $F(1, 68) = 2.23$, $p = \text{ns}$, or D-KEFS switching fluency, $F(1, 68) = 0.694$, $p = \text{ns}$.

Memory

Measures of verbal learning encoding on the CVLT-II were not significantly different for the total recall across the four trials, $F(1, 68) = 0.108$, $p = \text{ns}$. The short delay free recall of the CVLT-II revealed better performance for musicians relative to non-musicians, $F(1, 69) = 3.99$, $p < 0.05$ (see **Table 1** for means), but no significant group differences for CVLT-II long delay free recall, $F(1, 68) = 0.957$, $p = \text{ns}$. The groups also did not differ on immediate non-verbal recall of the WMS-III Visual Reproduction test (VR I), $F(1, 68) = 0.785$, $p = \text{ns}$, or the delayed recall of the Visual Reproduction (VR II), $F(1, 68) = 0.478$ $p = \text{ns}$. There were no significant differences in non-verbal memory recall between the musicians and non-musicians on ROCF immediate recall, $F(1, 68) = 0.006$, $p = \text{ns}$, or ROCF delayed recall, $F(1, 68) = 1.06$, $p = \text{ns}$ (**Table 1**).

Visuospatial

There were no significant differences in visuospatial constructions between the musicians and non-musicians on the ROCF copy, $F(1, 68) = 0.691$, $p = \text{ns}$, visuospatial working memory on the Spatial Span, $F(1, 68) = 0.345$, $p = \text{ns}$, or differences in capacity for complex visual form discrimination on the BVFD test, $F(1, 68) = 0.005$, $p = \text{ns}$. However, the musicians displayed better visuospatial judgment than the non-musicians on the JLO test, $F(1, 68) = 4.51$, $p = 0.037$ (see **Table 1** for means).

Frontal-executive

On the WCST test, there were no significant differences between musicians and non-musicians in terms of number of perseverations, $F(1, 68) = 0.507$, $p = \text{ns}$, or total categories completed, $F(1, 68) = 0.390$, $p = \text{ns}$. On the D-KEFS Tower task, there were no differences for the total score, $F(1, 68) = 0.052$, $p = \text{ns}$, or movement accuracy, $F(1, 68) = 0.106$, $p = \text{ns}$, although the non-musicians committed more rule violations during planning compared to the musicians, $F(1, 68) = 4.57$, $p < 0.05$.

Sensorimotor

The GP test did not reveal significantly better performance on manual dexterity for musicians relative to non-musicians. However, a trend emerged revealing faster performance on the GP for musicians for both the right dominant, $F(1, 68) = 3.43$, $p = 0.068$, and the left non-dominant hands, $F(1, 68) = 3.43$, $p = 0.071$. There were no significant differences between musicians and non-musicians on finger tapping speed for either the dominant right hand, $F(1, 68) = 0.874$, $p = \text{ns}$, or non-dominant left hand, $F(1, 68) = 2.79$, $p = \text{ns}$ (see **Table 1** for means). However, additional analyses on motor measures with strength of handedness (Edinburgh Quotient) as a covariate were conducted. When controlling for strength of handedness, there was a significant Group effect for the GP for the dominant hand, $F(1, 68) = 4.22$, $p = 0.044$ and approaching significance for the non-dominant hand, $F(1, 68) = 3.75$, $p = 0.057$. Finger tapping speed remained insignificant bilaterally.

Active musical participation in advanced age

Since only half of the musicians remained musically engaged in advanced age, we evaluated differences between the currently active musicians and those who were inactive at the time of the evaluation (inactive, $n = 16$; active, $n = 17$). Active musicians did not differ significantly from inactive musicians in terms of age, years of education or activity level as measured by the AAP (see **Table 2**). They also did not differ significantly

Table 2 | Means (SDs) scaled scores and significance for inactive and active musicians.

	Inactive musicians ($n = 16$)	Active musicians ($n = 17$)	F	Sig. ($p < 0.05$)	Effect size
Age	67.50 (5.03)	69.35 (3.76)	1.45	0.238	0.047
Education	16.75 (1.48)	17.12 (1.49)	0.502	0.484	0.016
AAP	45.31 (5.99)	45.35 (8.05)	0.000	0.987	0.000
ROCF delay recall	10.06 (3.33)	11.82 (2.53)	2.94	0.096	**0.087**
D-KEFS letter fluency	12.13 (3.50)	14.06 (3.33)	2.65	0.114	**0.079**
WAIS-III LNS	11.94 (2.21)	12.77 (2.11)	1.21	0.279	0.038
CVLT-II SDFR	0.594 (0.757)	0.676 (0.737)	0.102	0.751	0.003
Benton JLO	55.81 (3.88)	57.17 (3.15)	1.24	0.275	0.038
Tower – rule violation	10.88 (0.342)	10.94 (0.242)	0.416	0.524	0.013

AAP, Adelaide activities profile; WAIS-III, Wechsler adult intelligence scale third edition; D-KEFS, Delis–Kaplan executive function system; CVLT-II, California verbal learning test second edition; SDFR, short delay free recall; LNS, letter-number sequencing; JLO, judgment of line orientation; ROCF, Rey Osterrieth complex figure. AAP out of maximum 63; JLO out of a maximum of 60 items; CVLT in z score deviations from the mean.

$p < 0.05$.

in terms of age of musical acquisition, $F(1, 32) = 1.53$, $p =$ ns [mean $(SD)_{active} = 8.41(2.89)$; mean $(SD)_{inactive} = 10.19$ (5.16)], or formal years of musical training, $F(1, 32) = 2.86$ $p =$ ns [mean $(SD)_{active} = 4.65$ (2.98); mean $(SD)_{inactive} = 3.31(1.08)$]. Consistent with their continuation in musical activities in advanced age, active musicians devoted significantly more years to musical participation than inactive musicians $F(1, 32) = 45.89$ $p < 0.001$ [mean $(SD)_{active} = 54.35$ (16.15); $mean_{inactive} = 18.56$ (14.05)].

There were no significant differences between active and inactive musicians on verbal IQ estimates, neuropsychological measures, or for the specific measures that discriminated between non-musicians and musicians. However, a general trend emerged revealing better performance for active musicians relative to inactive musicians (see **Table 2** for means and effect sizes). The delayed recall of the ROCF and D-KEFS letter fluency emerged with the largest effect sizes explaining 8.7% and 7.9% (**Table 2**) respectively, of the between subjects variance, with significance levels likely influenced by the small sample sizes.

Results of partition analyses of music data

The effect sizes for partition trees are summarized in **Table 3**, in order from smallest to largest cross-validated R^2 (f^2). Cross-validated versions of effect size avoid over fitting, common in non-parametric models (i.e. models not restricted to *linear* functions). Using Cohen's (1988) convention of effect size f^2, 0.02, 0.15, and 0.35 are *small*, *medium*, and *large*. Two of the partition trees evaluating neuropsychological measures of significance for the musicians only have medium effect sizes, and are highlighted below.

Table 3 | Effect sizes of all partition analyses.

Dependent variable	Fivefolded cross-validated R^2 (%)	Effect size, f^2
MUSICIANS ONLY		
Judgment line orientation	15	0.18
Letter-number sequencing	14	0.16
Tower rule violations	0	0.00
Letter fluency	0	0.00
CVLT-II SDFR	0	0.00
Grooved pegboard – dominant hand	29	0.21
Grooved pegboard – non-dominant hand	28	0.20

The partition trees for JLO (**Figure 1**), LNS (**Figure 2**), and GP dominant and non-dominant hands (**Figures 3** and **4**) demonstrated the largest effect sizes for the models of musicians with $f^2 = 0.18$, 0.16, 0.21, and 0.20 respectively. Partition trees for CVLT-SDFR, Letter Fluency, and Tower were not significant for musicians. The musicians with higher education (i.e., greater than 17 years) had higher JLO scores (mean = 58.19, SD = 2.43) than the less educated musicians (mean = 54.94, SD = 3.75), while general activity level did not reliable predict JLO performance for the more educated. Among the less educated musicians, musicians with recent musical activity had higher scores (mean = 56.1, SD = 3.04) than those who did not actively play in advanced age (mean = 53.9, SD = 4.17). The LNS partition tree revealed that musicians with earlier age of acquisition (less than 9 years of age) had better verbal working memory functions (mean = 13.15, SD = 2.01) than musicians with age of acquisition after 9 years of age (mean = 11.28, SD = 1.94). Once again, general activity level did not reliably predict LNS performance. Among the older (>70 years of age) musicians, those with education greater than 17 years had higher GP dominant hand scores (mean = 8.4, SD = 1.14) than those with less than 17 years of education (mean = 6.3, SD = 1.5). However, among the older musicians with less than 17 years of education, active musical participation subtly enhanced non-dominant hand GP performance (mean = 6.6, SD = 0.894) relative to inactivity (mean = 6.4, SD = 1.52), although age less than 70 and education greater than 17 years was the best predictor of high GP performance.

DISCUSSION

The results of the current study reveal that older adults (59–80 years) who acquired music early in life and maintained musical activities for an extended period of time (minimum 10 years; mean 37 years), outperformed older control adults in non-musical cognitive domains of verbal working memory, verbal memory, verbal fluency, visuospatial, and planning functions. When accounting for strength of handedness, the musicians also outperformed

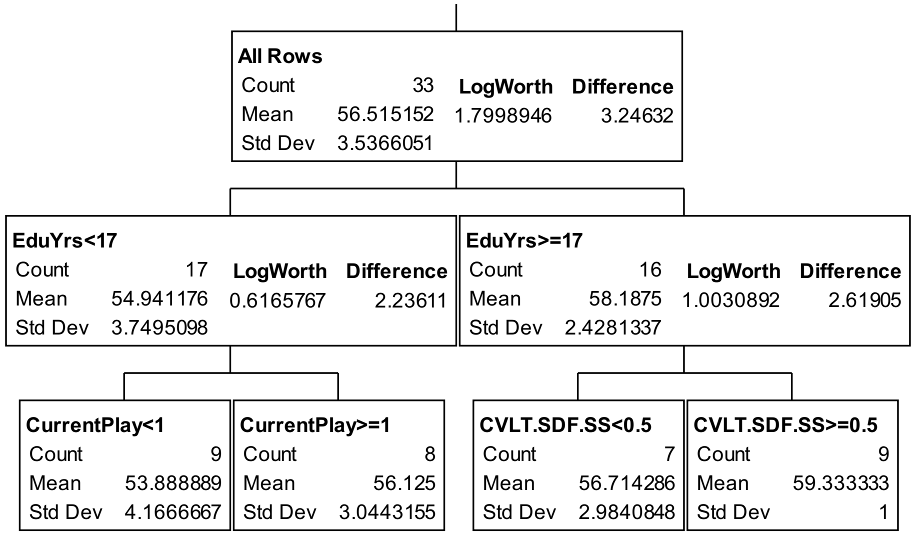

FIGURE 1 | Partition analysis judgment line orientation for musicians.

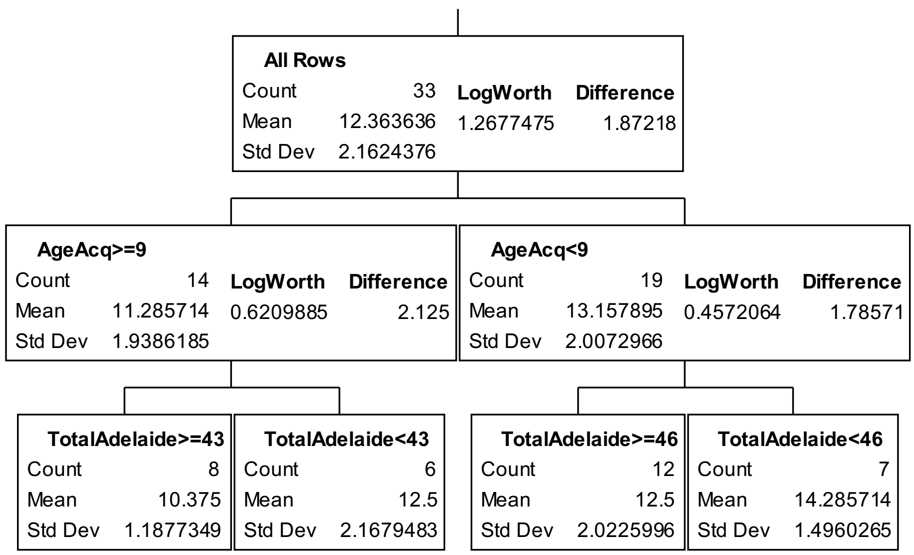

FIGURE 2 | Partition analysis for letter-number sequencing for musicians.

non-musicians on sensorimotor integration. From an early age, musicians engage in intensive practice involving repetitive visual translation of musical notation into spatiotemporal aspects of skilled movements that create the sound of music. Thus, the cognitive domains enhanced in the amateur musicians in our study match the demands of musical skill acquisition and training. Similarly, voxel-by-voxel morphometry has revealed gray matter volume enhancements in motor, auditory, and visuospatial brain regions for musicians (Gaser and Schlaug, 2003).

Furthermore, the cognitive domains of significance in our current study overlap with our previously reported findings in an independent sample of aging adults (60–83 years of age), although specific tests administered were different and replication was not identical (Hanna-Pladdy and Mackay, 2011). The most striking difference between our two studies was the type of memory performance enhanced in musicians, and was partly related to inclusion of a more sensitive verbal memory test in the current study. While we did not find differences on verbal memory in the first study utilizing the short version of the CVLT-II, we did find higher verbal recall for musicians after a brief delay in the current study when utilizing the long CVLT-II which is a more sensitive test and also requires semantic organizational strategies. This result corresponds to previously reported differences in young musicians on a Korean version of this verbal memory test (Chan et al., 1998; Ho et al., 2003). In addition to verbal memory enhancement for older musicians, we also found differences in verbal fluency and

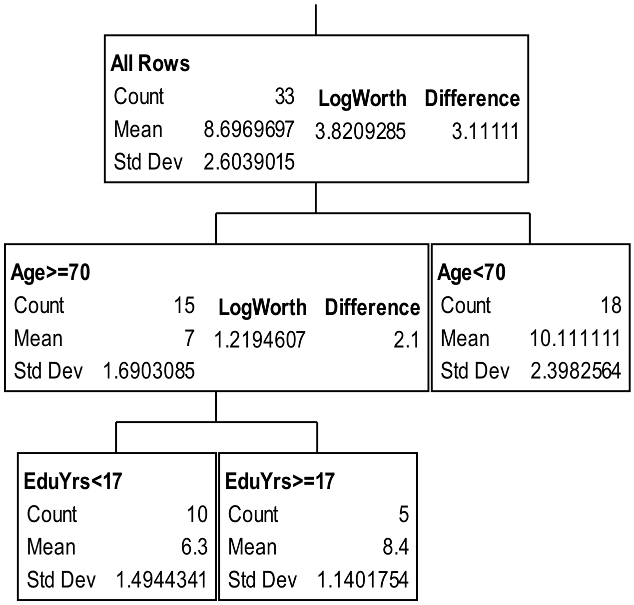

FIGURE 3 | Partition analysis for grooved pegboard dominant hand scaled scores.

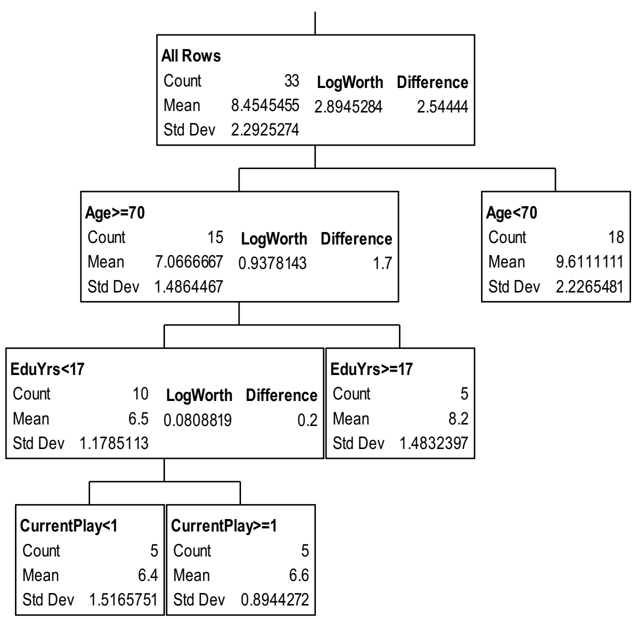

FIGURE 4 | Partition analysis for grooved pegboard non-dominant hand scaled scores.

verbal working memory functions. The overlap between language and verbal functions with musical networks has been given careful consideration especially given the auditory demands of music processing (Fujioka et al., 2006; Patel and Iversen, 2007; Forgeard et al., 2008).

Functional imaging results have revealed auditory-sensorimotor integration in musicians, whereby there is co-activation of a musical network whether musicians are passively processing auditory properties of music or providing the motor response (Lotze et al., 2003; Bangert et al., 2006). Consequently, it is not surprising that similar to our study results, there has been consistent demonstration of musical enhancement in auditory processing given the close link to musical cognitive demands (Pantev et al., 1998; Fujioka et al., 2006; Parbery-Clark et al., 2011). The neural basis of these enhancements are supported by large activations in the left hemisphere evident for musicians in prefrontal areas, supramarginal gyrus, and temporal areas varying depending on the musical cognitive processing requirements (Koelsch et al., 2005). These brain differences have been utilized as support for the presence of brain plasticity in longitudinal studies revealing differences in expected brain regions closely tied to musical skills, but also in brain regions unrelated to those skills responsible for multimodal integration (Hyde et al., 2009). These regions might possibly underlie the cognitive advantages in visuospatial processing identified in our study. At least one study has provided evidence suggesting that visuospatial advantages may be uniquely processed by a highly developed left hemisphere in musicians (Sluming et al., 2007). Although visuospatial advantages in musicians have not been consistently reported, there is a growing body of literature supporting non-verbal and visuospatial enhancements, but the underlying neural mechanisms are poorly understood (Costa-Giomi et al., 2001; Brochard et al., 2004; Forgeard et al., 2008).

Despite the obvious skilled movements associated with musical training, we did not find statistically significant differences between the groups for finger tapping speed which is in contrast to previously reported results (Jancke et al., 1997). It is conceivable that other age-related factors such as arthritis may have obscured significance in the motor domain, or perhaps the findings were not robust because musicians were not required to be musically active at the time of the study. This hypothesis is partially supported by the results of the partition analyses for sensorimotor functions. In addition to inactive musical participation in recent years, our participants differed from other studies in that they were all amateurs and therefore engaged in less extensive musical training which may have influenced the motor findings. Nonetheless, when controlling for strength of handedness, we did find differences in sensorimotor functions. This is consistent with evidence for expansion of cortical representations for musicians related to length of practice (Elbert et al., 1995). Also, gray matter differences between musicians and non-musicans has been identified extending from the premotor region to the primary somatosensory cortex into the anterior parietal lobe attributed to skill acquisition and practice (Gaser and Schlaug, 2003). Conversely, there is clear evidence that reduction of cortical representational areas accompanies reduced skilled use, in support of our less than robust motor findings for older adults with less recent activity (Liepert et al., 1995).

Despite group differences between musicians and non-musicians on a range of cognitive measures, partition analyses evaluating predictors of cognitive performance for the musical group only revealed significance on two tasks, JLO and LNS. These cognitive tasks span across both verbal and visuospatial domains, but both requiring fluid abilities. Similar to another recent study, we found verbal working memory but not spatial working memory differences and may be partially explained by differences in test sensitivity (Parbery-Clark et al., 2011). The finding that age of musical acquisition before age 9 predicts enhanced performance in verbal working memory functions in advanced age, supports the model of sensitive periods for auditory and language circuits. The maintenance of cognitive enhancements many years later irrespective of continued participation in musical activity, suggests that neural circuits during this critical period may be altered permanently. Indeed, increased size for the corpus callosum in musicians has been documented, but in particular in the anterior corpus callosum in the musicians who began musical training before the age of 7 (Schlaug et al., 1995). Consistent with our findings, this suggests that there is a maturation period within the first decade of life. However, since continued music participation predicted visuospatial functions, this raises the question of different sensitive periods for cognitive stimulation, or alternatively whether continued experience can alter connectivity patterns with the architectural constrains established during earlier sensitive periods (Knudsen, 2004). However, our results do not allow us to tease apart the reason for this association, and it is plausible that older individuals with enhanced cognitive sensory abilities in advanced age are more likely to persist with musical activity.

Education proved to have the greatest impact on performance in visuospatial judgment for musicians, although our results revealed that recent musical participation could compensate for lower educational levels (Caparelli-Daquer et al., 2009). These results imply that musical training may be considered an educational opportunity serving as additional cognitive stimulation outside of the traditional academic domain. Structural and functional changes in white matter, dorsolateral frontal, and inferior frontal regions offer strong support for the enhancements in frontal-networks functions (i.e., working memory, cognitive flexibility, and planning functions) for the musicians in our study (Hyde et al., 2009). Moreover, one longitudinal study with random assignment of young children into musical and non-musical groups, reported improvement in executive functions after only 20 days of musical training with additional neural evidence from corresponding ERP (Moreno et al., 2011a). It is conceivable that music training influences domain specific processes in verbal and auditory functions, but also domain-general processes such as attention and executive functioning (Hannon and Trainor, 2007). This hypothesis is supported by the results of our previous study which revealed that performance on a task requiring cognitive flexibility was the best cognitive predictor of musical status (Hanna-Pladdy and Mackay, 2011).

Many activities that are associated with cognitive stimulation may also increase social interactions and physical activity, making it difficult to discern whether it is the cognitive, social or physical aspect of the activity that is yielding the beneficial effect. Because of these challenges and the difficulty in randomly assigning subjects to musical and non-musical groups, there is a need to try and determine statistically whether musical effects are related to learning effects versus a population bias (i.e., highly educated individuals are more likely to engage in musical activities), or effect of increased general lifestyle activities (Schellenberg, 2004; Green and Bavelier, 2008). Our previous study accounted for the variance in cognitive aging variability related to physical exercise and demonstrated significant contributions to cognition from musical activity above that attributed to physical activity (Hanna-Pladdy and Mackay, 2011). Results of our partition analyses from the current study reveal that participation in general activities was not a reliable predictor of cognitive performance, and that musicians did not differ in general lifestyle activity engagement relative to non-musicians, making this hypothesis less plausible. However, there are several limitations which should be considered in interpretation of the current findings. First and foremost, while the current study controlled for general lifestyle activities, future studies will be needed to compare musical training to other specific leisure activities. Furthermore, given our small sample size, multiple comparisons is a limitation of this exploratory study especially since musicians only revealed statistical significance on five of the neuropsychological measures. Therefore, all results should be verified with prospective large studies with specific hypotheses generated based on our findings.

In summary, there is mounting evidence supporting training-induced brain changes from musical experience that can potentially transfer to non-musical cognitive abilities and influence cognitive functioning across the lifespan into advanced age (for review see Jancke, 2009a,b). However, further research is needed to fully understand the developmental mechanisms, and to tease apart the relative contributions from "nature and nurture" to musical skills and cognitive differences between musicians and non-musicians. By understanding differences in sensitive periods, and the range of activities that may stimulate cognition, we can gain deeper insight into the critical role that experience plays in shaping the brain across the lifespan. It remains unclear whether musical acquisition in adulthood affords any cognitive or neural advantages. Furthermore, longitudinal and neuroimaging studies of aging are needed to evaluate whether musicians may have enhanced cognitive reserve enabling them to better compensate for age-related cognitive declines, and reduce or delay the onset of cognitive decline or development of a neurodegenerative process.

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REFERENCES

Anstey, K. J., and Smith, G. A. (1999). Interrelationships among biological markers of aging, health, activity, acculturation, and cognitive performance in late adulthood. *Psychol. Aging* 14, 605–618.

Bangert, M., Peschel, T., Schlaug, G., Rotte, M., Drescher, D., Hinrichs, H., Heinze, H. J., and Altenmuller, E. (2006). Shared networks for auditory and motor processing in professional pianists: evidence from fMRI conjunction. *Neuroimage* 30, 917–926.

Benton, A., Sivan, A., Hamsher, K., Varney, N., and Spreen, O. (ed.). (1994). *Contributions to Neuropsychological Assessment: A Clinical Manual.* New York: Oxford University Press.

Bezzola, L., Merillat, S., Gaser, C., and Jancke, L. (2011). Training-induced neural plasticity in golf novices. *J. Neurosci.* 31, 12444–12448.

Bezzola, L., Merillat, S., and Jancke, L. (2012). The effect of leisure activity golf practice on motor imagery: an fMRI study in middle adulthood. *Front. Hum. Neurosci.* 6:67. doi:10.3389/fnhum.2012.00067

Bialystok, E., Craik, F. I., and Freedman, M. (2007). Bilingualism as a protection against the onset of symptoms of dementia. *Neuropsychologia* 45, 459–464.

Boyke, J., Driemeyer, J., Gaser, C., Buchel, C., and May, A. (2008). Training-induced brain structure changes in the elderly. *J. Neurosci.* 28, 7031–7035.

Brochard, R., Dufour, A., and Despres, O. (2004). Effect of musical expertise on visuospatial abilities: evidence from reaction times and mental imagery. *Brain Cogn.* 54, 103–109.

Cabeza, R., Anderson, N. D., Locantore, J. K., and Mcintosh, A. R. (2002). Aging gracefully: compensatory brain activity in high-performing older adults. *Neuroimage* 17, 1394–1402.

Caparelli-Daquer, E. M., Oliveira-Souza, R., and Moreira Filho, P. F. (2009). Judgment of line orientation depends on gender, education, and type of error. *Brain Cogn.* 69, 116–120.

Chan, A. S., Ho, Y. C., and Cheung, M. C. (1998). Music training improves verbal memory. *Nature* 396, 128.

Clark, M. S., and Bond, M. J. (1995). The Adelaide Activities Profile: a measure of the life-style activities of elderly people. *Aging (Milano)* 7, 174–184.

Cohen, J. (1988). *Statistical Power Analysis for the Behavioral Sciences*, 2nd Edn. Hillsdale: Lawrence Erlbaum Associates.

Costa-Giomi, E., Gilmour, R., Siddell, J., and Lefebvre, E. (2001). Absolute pitch, early musical instruction, and spatial abilities. *Ann. N.Y. Acad. Sci.* 930, 394–396.

Craik, F. I., Bialystok, E., and Freedman, M. (2010). Delaying the onset of Alzheimer disease: bilingualism as a form of cognitive reserve. *Neurology* 75, 1726–1729.

Delis, D. C., Kramer, J. H., Kaplan, E., and Holdnack, J. (2004). Reliability and validity of the Delis-Kaplan Executive Function System: an update. *J. Int. Neuropsychol. Soc.* 10, 301–303.

Delis, D. C., Kramer, J. H., Kaplan, E., and Ober, B. A. (2000). *California Verbal Learning Test.* San Antonio, TX: Psychological Corporation.

Elbert, T., Pantev, C., Wienbruch, C., Rockstroh, B., and Taub, E. (1995). Increased cortical representation of the fingers of the left hand in string players. *Science* 270, 305–307.

Fillit, H. M., Butler, R. N., O'Connell, A. W., Albert, M. S., Birren, J. E., Cotman, C. W., Greenough, W. T., Gold, P. E., Kramer, A. F., Kuller, L. H., Perls, T. T., Sahagan, B. G., and Tully, T. (2002). Achieving and maintaining cognitive vitality with aging. *Mayo Clin. Proc.* 77, 681–696.

Folstein, M. F., Folstein, S. E., and Mchugh, P. R. (1975). "Mini-mental state." A practical method for grading the cognitive state of patients for the clinician. *J. Psychiatr. Res.* 12, 189–198.

Forgeard, M., Winner, E., Norton, A., and Schlaug, G. (2008). Practicing a musical instrument in childhood is associated with enhanced verbal ability and nonverbal reasoning. *PLoS ONE* 3, e3566. doi:10.1371/journal.pone.0003566

Fujioka, T., Ross, B., Kakigi, R., Pantev, C., and Trainor, L. J. (2006). One year of musical training affects development of auditory cortical-evoked fields in young children. *Brain* 129, 2593–2608.

Gaser, C., and Schlaug, G. (2003). Brain structures differ between musicians and non-musicians. *J. Neurosci.* 23, 9240–9245.

Grant, D. A., and Berg, E. (1948). A behavioral analysis of degree of reinforcement and ease of shifting to new responses in a Weigl-type card-sorting problem. *J. Exp. Psychol.* 38, 404–411.

Green, C. S., and Bavelier, D. (2008). Exercising your brain: a review of human brain plasticity and training-induced learning. *Psychol. Aging* 23, 692–701.

Greenough, W. T., Mcdonald, J. W., Parnisari, R. M., and Camel, J. E. (1986). Environmental conditions modulate degeneration and new dendrite growth in cerebellum of senescent rats. *Brain Res.* 380, 136–143.

Grober, E., Buschke, H., Crystal, H., Bang, S., and Dresner, R. (1988). Screening for dementia by memory testing. *Neurology* 38, 900–903.

Hall, C. B., Lipton, R. B., Sliwinski, M., Katz, M. J., Derby, C. A., and Verghese, J. (2009). Cognitive activities delay onset of memory decline in persons who develop dementia. *Neurology* 73, 356–361.

Hanna-Pladdy, B., and Mackay, A. (2011). The relation between instrumental musical activity and cognitive aging. *Neuropsychology* 25.

Hannon, E. E., and Trainor, L. J. (2007). Music acquisition: effects of enculturation and formal training on development. *Trends Cogn. Sci.* 11, 466–472.

Ho, Y. C., Cheung, M. C., and Chan, A. S. (2003). Music training improves verbal but not visual memory: cross-sectional and longitudinal explorations in children. *Neuropsychology* 17, 439–450.

Hyde, K. L., Lerch, J., Norton, A., Forgeard, M., Winner, E., Evans, A. C., and Schlaug, G. (2009). The effects of musical training on structural brain development: a longitudinal study. *Ann. N.Y. Acad. Sci.* 1169, 182–186.

Jacova, C., Kertesz, A., Blair, M., Fisk, J. D., and Feldman, H. H. (2007). Neuropsychological testing and assessment for dementia. *Alzheimers Dement.* 3, 299–317.

Jaeggi, S. M., Buschkuehl, M., Jonides, J., and Perrig, W. J. (2008). Improving fluid intelligence with training on working memory. *Proc. Natl. Acad. Sci. U.S.A.* 105, 6829–6833.

Jancke, L. (2009a). Music drives brain plasticity. *F1000 Biol. Rep.* 1, 78.

Jancke, L. (2009b). The plastic human brain. *Restor. Neurol. Neurosci.* 27, 521–538.

Jancke, L., Schlaug, G., and Steinmetz, H. (1997). Hand skill asymmetry in professional musicians. *Brain Cogn.* 34, 424–432.

Kaplan, E., Goodglass, H., and Weintraub, S. (1983). *Boston Naming Test.* Philadelphia: Lee & Febiger.

Karbach, J., and Kray, J. (2009). How useful is executive control training? Age differences in near and far transfer of task-switching training. *Dev. Sci.* 12, 978–990.

Knudsen, E. I. (2004). Sensitive periods in the development of the brain and behavior. *J. Cogn. Neurosci.* 16, 1412–1425.

Koelsch, S., Fritz, T., Schulze, K., Alsop, D., and Schlaug, G. (2005). Adults and children processing music: an fMRI study. *Neuroimage* 25, 1068–1076.

Kramer, A. F., Bherer, L., Colcombe, S. J., Dong, W., and Greenough, W. T. (2004). Environmental influences on cognitive and brain plasticity during aging. *J. Gerontol. A Biol. Sci. Med. Sci.* 59, M940–M957.

Liepert, J., Tegenthoff, M., and Malin, J. P. (1995). Changes of cortical motor area size during immobilization. *Electroencephalogr. Clin. Neurophysiol.* 97, 382–386.

Lotze, M., Scheler, G., Tan, H. R., Braun, C., and Birbaumer, N. (2003). The musician's brain: functional imaging of amateurs and professionals during performance and imagery. *Neuroimage* 20, 1817–1829.

Loui, P., Kroog, K., Zuk, J., Winner, E., and Schlaug, G. (2011). Relating pitch awareness to phonemic awareness in children: implications for tone-deafness and dyslexia. *Front. Psychol.* 2:111. doi:10.3389/fpsyg.2011.00111

Moreno, S., Bialystok, E., Barac, R., Schellenberg, E. G., Cepeda, N. J., and Chau, T. (2011a). Short-term music training enhances verbal intelligence and executive function. *Psychol. Sci.* 22, 1425–1433.

Moreno, S., Friesen, D., and Bialystok, E. (2011b). Effect of music training on promoting preliteracy skills: preliminary causal evidence. *Music Percept.* 29, 165–172.

Morgan, C. D., and Baade, L. E. (1997). Neuropsychological testing and assessment scales for dementia of the Alzheimer's type. *Psychiatr. Clin. North Am.* 20, 25–43.

Newson, R. S., and Kemps, E. B. (2005). General lifestyle activities as a predictor of current cognition and cognitive change in older adults: a cross-sectional and longitudinal examination. *J. Gerontol. B. Psychol. Sci. Soc. Sci.* 60, P113-120.

Oldfield, R. C. (1971). The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia* 9, 97–113.

Osterrieth, P. A. (1944). Test of copying a complex figure; contribution to the study of perception and memory. *Arch. Psychol.* 30, 206–356.

Ott, C. G., Langer, N., Oechslin, M., Meyer, M., and Jancke, L. (2011). Processing of voiced and unvoiced acoustic stimuli in musicians. *Front. Psychol.* 2, 195. doi: 10.3389/fpsyg.2011.00195

Pantev, C., Oostenveld, R., Engelien, A., Ross, B., Roberts, L. E., and Hoke, M. (1998). Increased auditory cortical representation in musicians. *Nature* 392, 811–814.

Pantev, C., Ross, B., Fujioka, T., Trainor, L. J., Schulte, M., and Schulz, M. (2003). Music and learning-induced cortical plasticity. *Neurosci. Music* 999, 438–450.

Parbery-Clark, A., Strait, D. L., Anderson, S., Hittner, E., and Kraus, N. (2011). Musical experience and the aging auditory system: implications for cognitive abilities and hearing speech in noise. *PLoS ONE* 6, e18082. doi:10.1371/journal.pone.0018082

Patel, A. D. (2011). Why would musical training benefit the neural encoding of speech? The OPERA hypothesis. *Front. Psychol.* 2:142. doi:10.3389/fpsyg.2011.00142

Patel, A. D., and Iversen, J. R. (2007). The linguistic benefits of musical abilities. *Trends Cogn. Sci.* 11, 369–372.

Penhune, V., Watanabe, D., and Savion-Lemieux, T. (2005). The effect of early musical training on adult motor performance: evidence for a sensitive period in motor learning. *Ann. N.Y. Acad. Sci.* 1060, 265–268.

Reitan, R. M., and Wolfson, D. (1993). *Halstead-Reitan Neuropsychological Battery*. Tuscon, AZ: Neuropsychology Press.

Rey, A., and Osterrieth, P. (1939). Dominance of the mental organism over the physical; the reaction of closing the eyes. *Arch. Psychol.* 27, 157–171.

Rey, A., and Osterrieth, P. A. (1993). Translations of excerpts from Andre Rey's Psychological examination of traumatic encephalopathy and P. A. Osterrieth's The Complex Figure Copy Test. *Clin. Neuropsychol.* 7, 4–21.

Salthouse, T. A. (2004). Localizing age-related individual differences in a hierarchical structure. *Intelligence* 32, 541–561.

SAS, I. I. (2008). *JMP 8 Introductory Guide*. Cary, NC: SAS Institute Inc.

Scarmeas, N., Zarahn, E., Anderson, K. E., Habeck, C. G., Hilton, J., Flynn, J., Marder, K. S., Bell, K. L., Sackeim, H. A., Van Heertum, R. L., Moeller, J. R., and Stern, Y. (2003). Association of life activities with cerebral blood flow in Alzheimer disease: implications for the cognitive reserve hypothesis. *Arch. Neurol.* 60, 359–365.

Schellenberg, E. G. (2004). Music lessons enhance IQ. *Psychol. Sci.* 15, 511–514.

Schellenberg, E. G., and Peretz, I. (2008). Music, language and cognition: unresolved issues. *Trends Cogn. Sci.* 12, 45–46.

Schlaug, G., Jancke, L., Huang, Y., Staiger, J. F., and Steinmetz, H. (1995). Increased corpus callosum size in musicians. *Neuropsychologia* 33, 1047–1055.

Schlaug, G., Norton, A., Overy, K., and Winner, E. (2005). Effects of music training on the child's brain and cognitive development. *Ann. N.Y. Acad. Sci.* 1060, 219–230.

Shahin, A. J. (2011). Neurophysiological influence of musical training on speech perception. *Front. Psychol.* 2:126. doi:10.3389/fpsyg.2011.00126

Sluming, V., Barrick, T., Howard, M., Cezayirli, E., Mayes, A., and Roberts, N. (2002). Voxel-based morphometry reveals increased gray matter density in Broca's area in male symphony orchestra musicians. *Neuroimage* 17, 1613–1622.

Sluming, V., Brooks, J., Howard, M., Downes, J. J., and Roberts, N. (2007). Broca's area supports enhanced visuospatial cognition in orchestral musicians. *J. Neurosci.* 27, 3799–3806.

Springer, M. V., Mcintosh, A. R., Winocur, G., and Grady, C. L. (2005). The relation between brain activity during memory tasks and years of education in young and older adults. *Neuropsychology* 19, 181–192.

Stern, C., and Munn, Z. (2010). Cognitive leisure activities and their role in preventing dementia: a systematic review. *Int. J. Evid. Based Healthc.* 8, 2–17.

Valenzuela, M. J., and Sachdev, P. (2006). Brain reserve and cognitive decline: a non-parametric systematic review. *Psychol. Med.* 36, 1065–1073.

Verghese, J., Lipton, R. B., Katz, M. J., Hall, C. B., Derby, C. A., Kuslansky, G., Ambrose, A. F., Sliwinski, M., and Buschke, H. (2003). Leisure activities and the risk of dementia in the elderly. *N. Engl. J. Med.* 348, 2508–2516.

Wechsler, D. (1997a). *WAIS-III: Administration and Scoring Manual*. San Antonio: The Psychological Corporation.

Wechsler, D. (1997b). *Wechsler Memory Scale - Third Edition Manual*. San Antonio, TX: Psychological Corporation.

Wilson, R., Barnes, L., and Bennett, D. (2003). Assessment of lifetime participation in cognitively stimulating activities. *J. Clin. Exp. Neuropsychol.* 25, 634–642.

Zendel, B. R., and Alain, C. (2012). Musicians experience less age-related decline in central auditory processing. *Psychol. Aging* 27, 410–417.

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Training-induced compensation versus magnification of individual differences in memory performance

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Do individuals with higher levels of task-relevant cognitive resources gain more from training, or do they gain less? For episodic memory, empirical evidence is mixed. Here, we revisit this issue by applying structural equation models for capturing individual differences in change to data from 108 participants aged 9–12, 20–25, and 65–78 years. Participants learned and practiced an imagery-based mnemonic to encode and retrieve words by location cues. Initial mnemonic instructions reduced between-person differences in memory performance, whereas further practice after instruction magnified between-person differences. We conclude that strategy instruction compensates for inefficient processing among the initially less able. In contrast, continued practice magnifies ability-based between-person differences by uncovering individual differences in memory plasticity.

Keywords: memory plasticity, magnification, amplification, compensation, associative memory, aptitude by treatment interactions

INTRODUCTION

A long-standing debate in psychometrically oriented developmental and non-developmental intelligence research deals with the issue of whether intelligence equals learning efficiency (e.g., Sternberg and Detterman, 1986; Neisser et al., 1996; Garlick, 2002) and with the related issue of aptitude by treatment interactions (e.g., Ferguson, 1956; Cronbach, 1957; Sullivan, 1964). In other words, do individuals with higher levels of task-relevant cognitive resources gain more from training? For the cognitive ability focused on in this article, episodic memory, the empirical evidence is still mixed: while positive correlations between cognitive ability and gains from instructions and practice on cognitive tasks have been reported (e.g., Kliegl et al., 1990; Verhaeghen and Marcoen, 1996; Kwon and Lawson, 2000), negative correlations are also common (e.g., Gaultney et al., 1996; Cox, 2001). These different findings have consequently given rise to competing views on interindividual differences in training gains, which are most notably represented by the magnification and compensation accounts.

The magnification view is prominent for interpreting the increase in adult age differences after mnemonic training, such as after instructions and practice in the Method of Loci (Kliegl et al., 1990; Verhaeghen and Marcoen, 1996). In adult lifespan samples, both cognitive abilities (Schaie, 1996; Li et al., 2004; Rönnlund et al., 2005) and gains from mnemonic training (Verhaeghen et al., 1992) decline with age. Moreover, cognitive abilities are usually positively related to gains from mnemonic training (Kliegl et al., 1990; Lindenberger et al., 1992; Verhaeghen and Marcoen, 1996). This pattern of findings suggests that individual and age-related differences in gains from cognitive training can be explained by initial differences in cognitive resources available to acquire, implement, and sharpen effortful cognitive strategies. The magnification account comes with three predictions. First, group differences should be magnified after training, in the sense that groups starting out higher will gain more. Second, within groups, gains from cognitive training should correlate positively with cognitive abilities as well as with initial performance. Third, the magnitude of interindividual differences should increase as a function of training because differences between the high- and low-performing individuals should be greater after training than at baseline assessment. The magnification view has gained widespread acceptance in the cognitive aging community (e.g., Kramer and Willis, 2002; Baltes et al., 2006; for reviews see Verhaeghen et al., 1992; Verhaeghen and Kliegl, 2000, see also Bjorklund et al., 1997).

In contrast, the basic reasoning in favor of the competing compensation account is that individuals with good assets are already functioning at optimal levels and thus have less room for improvement. In the case of mnemonic strategy training, for example, individuals who already apply an efficient and honed mnemonic strategy that yields good memory might gain little from being taught another efficient strategy, as compared to individuals who apply an inefficient or no strategy. Thus, the compensation account predicts that gains from cognitive training correlate negatively with cognitive abilities and initial performance, and that age differences, and other interindividual differences, are reduced after training. Notably, supporting data for the compensation model appears to be more prevalent in the literature on child development (e.g., Gaultney et al., 1996; Cox, 2001; see also Bjorklund and Douglas, 1997; Schneider, 2012).

Though both the magnification and the compensation views make clear and competing predictions, their simultaneous presence also gives room for *post-hoc* explanations of empirical observations because neither account includes predictions for the conditions under which it may or may not be applicable. Here, we rely on the recently introduced theoretical distinction between flexibility and plasticity (Lövdén et al., 2010; see also Baltes, 1987; Will et al., 2008) to arrive at such discriminating predictions, and then test our predictions in a sufficiently large data set on lifespan differences in memory plasticity.

According to Lövdén et al. (2010), flexibility denotes the capacity to optimize performance within the limits of the brain's currently imposed structural constraints. That is, the cognitive system is characterized as having a range of existing (i.e., previously formed) representational states available, and to constantly adapt to environmental demands by assuming such states. This notion of a range of performance and function is similar to the concept of baseline reserve capacity (e.g., Baltes, 1987), and points to the malleability of cognitive performance through environmental support (e.g., instructions). In contrast, plasticity denotes the capacity for changes in the possible range of cognitive performance enabled by flexibility (cf. Baltes, 1987; Baltes et al., 2006). In other words, adaptations of the brain to environmental changes do not uniquely define plasticity, but rather constitute a fundamental property of experience and a starting point of plasticity. Whereas flexibility refers to the adaptation of a pre-existing behavioral repertoire, plasticity refers to the expansion of this repertoire following structural cerebral change.

We propose that the distinction between flexibility and plasticity permits predictions about the empirical conditions under which compensation or magnification are more likely to occur. First, performance gains primarily acquired by making use of flexibility are likely to display a pattern consistent with the compensation model. If the brain's performance for a particular task is already optimized within current structural constraints, then nothing can be gained from altering the way that a task is executed, be it through instructions or through some other means. Hence, within the range of performance covered by flexibility, better performing individuals will gain less. In contrast, the situation is radically different if extensive practice pushes individuals beyond the current range of performance, thereby inducing plastic changes. In this case, the prevailing empirical pattern should be magnification because individual differences in baseline levels of performance and cognitive resources are, at least in part, a reflection of past manifestations of plasticity. Under such conditions, we expect that baseline performance will correlate positively with intervention-induced training gains.

To address this set of predictions, we reanalyzed data from a study previously reported by Brehmer et al. (2007; see also Brehmer et al., 2008). In this study, children, younger adults, and older adults were first taught and then allowed to practice memory performance with an interactive imagery mnemonic, akin to the Method of Loci (Bower, 1970). The mnemonic used is well suited for encoding and retrieving location-word paired-associates, which were the target of training. After initial assessment of performance, instruction sessions, and a post-instruction assessment of performance, an adaptive procedure, involving individual adjustment of presentation times, was used to produce a measurement space covering all age groups and the total practice phase (for details, see Brehmer et al., 2007). In addition, to assess baseline cognitive resources, Brehmer and colleagues (2007) also administered a psychometric battery of tasks measuring four cognitive abilities: perceptual speed, reasoning, episodic memory, and verbal knowledge. The present reanalysis goes beyond Brehmer and colleagues (2007, 2008) by addressing the predictions from the compensation and magnification views, and by applying statistical techniques (structural equation modeling; SEM) suitable for analyzing interindividual differences in performance changes as well as correlations between initial level and change. In contrast, previous reports of this data focused on age group differences (Brehmer et al., 2007) and maintenance (Brehmer et al., 2008) of mean performance.

To summarize, we assume that gains due to instructions in the mnemonic technique are primarily acquired through flexibility, as they recruit and configure existing resources, such as knowledge about memory strategies. In contrast, performance gains produced through subsequent practice primarily reflect plasticity. Specifically, during practice, all individuals are likely to perform the task in a qualitatively similar fashion, and performance improvements reflect changes in the possible range of cognitive performance. Based on these considerations, we hypothesized that instruction gains follow the prediction from the compensation view whereas practice gains follow the prediction from the magnification model.

MATERIALS AND METHODS

PARTICIPANTS

The sample consisted of 50 children aged 9–12 years ($M_{age} = 11.0$; $SD_{age} = 1.2$; 24 girls), 29 younger adults aged 20–25 years ($M_{age} = 22.5$; $SD_{age} = 0.6$; 15 women), and 29 older adults aged 65–78 years ($M_{age} = 66.9$; $SD_{age} = 3.7$; 14 women). Children either had received the elementary school's recommendation to attend, or were attending the German school type with the highest entry requirements after completion of elementary school (i.e., *Gymnasium*). Younger adults were students at Saarland University, Saarbrücken, Germany. Older adults were either auditors at Saarland University, participants in other continuing education programs, or both. All participants had normal, or corrected to normal, vision, and hearing. Participants were paid 7.5 Euro for each full hour of testing.

Table 1 summarizes scores on four cognitive composites representing performance on psychometric tests of perceptual speed, episodic memory, reasoning, and verbal knowledge as a function of age group. For a detailed description of these composites, see *Background assessment*. Importantly, the cognitive characteristics display the typical developmental dissociation of an inverted U-shape for the measures of broad fluid abilities (memory, perceptual speed, and reasoning), and a continuous age-related increase in verbal knowledge (e.g., Li et al., 2004). Thus, although the overall sample is positively selected (see Brehmer et al., 2007

Table 1 | Cognitive characteristics of the age groups.

Variable	Children		Younger adults		Older adults	
	M	*SD*	*M*	*SD*	*M*	*SD*
Perceptual speed	44.8	5.0	63.3	6.0	45.8	7.2
Paired-associates	49.9	10.4	55.2	7.8	45.1	9.0
Reasoning	46.4	7.5	59.7	8.3	46.4	9.0
Verbal knowledge	40.5	5.1	57.5	4.2	58.9	4.2

Note: Perceptual speed = unit-weighted composite of Digit Symbol Substitution (Wechsler, 1958) and Digit Letter; Reasoning = unit-weighted composite of Figural Analogies, Letter Series, and Practical Problems; Verbal knowledge = unit-weighted composite of Spot-a-Word and Vocabulary. All variables were scaled to the T-metric (M = 50; SD = 10), with the total sample providing reference values.

for details), it constitutes a satisfactory approximation of lifespan population trends in cognitive functioning.

MEMORY TASK

Materials

Every study list consisted of 16 location-word pairs. Sixteen generic common city locations (e.g., bakery and train station) were used. The 16 locations were recycled across the different lists. The presentation order of the location cues was separately randomized at encoding and retrieval, for each list in a new random order.

A total of 413 highly imaginable and concrete nouns were selected as memory materials from a pool of 1,200 words recorded by a professional radio speaker. Selection was based on a rating study with 10 children (7–9 years old) to reduce a possible confound of age differences in word knowledge (Brehmer et al., 2004). No word was administered more than once within a given session. Words were recycled over sessions with the following three constraints: (a) A word presented at a given session did not reappear in the next session; (b) within each list, the first three letters of all 16 words were different from each other to avoid errors during response entry; and (c) words presented at the pre-instruction, post-instruction and posttest assessments were not presented in any other sessions.

Experimental paradigm

During the encoding phase, the words constituting location cues were presented visually on a monitor, and to-be-learned words were presented over headphones. First, a blank screen was presented. Second, the location cue was presented. Third, the location cue was replaced by a fixation cross, and the to-be-learned word was presented. The time for the third phase was set to 10 s for pre-instruction and post-instruction sessions. For the practice sessions, an adaptive algorithm dynamically set the encoding time for each participant individually for each list. At the final session for each individual, memory performance was assessed at a fixed (across lists), but individualized, presentation rate (see *Individually Adaptive Practice*).

After all 16 location-word pairs had been presented participants started the recall phase by pressing the space bar. After that, an empty screen appeared for 0.5 s, followed by a location cue, which was presented for 5 s. After another 5 s, a rectangle appeared on the screen to signal the participants that responding was possible. Participants made their responses by entering the first three letters of the corresponding word. The response time window was 90 s. Participants went to the next location cue by pressing the enter bar. After recall of each list, participants were given feedback on their level of recall performance.

PROCEDURE

The general procedures can be dived into five phases: background assessment, baseline assessment, mnemonic instruction, post-instruction assessment, and individually adaptive practice, which ranged from 3 to 7 sessions (see **Table 2** for an overview of the study design).

Background assessment

In the first session, participants were administered a demographic questionnaire, tests of sensory acuity, and a psychometric battery of tests assessing perceptual speed, reasoning, paired-associates (episodic memory), and verbal knowledge (Lindenberger et al., 1993; see also Lövdén et al., 2004). A Macintosh SE30 computer equipped with a touch-sensitive screen was used for cognitive testing.

Table 2 | Outline of study design.

Phase of study	Number of sessions	Description	Lists observed	Lists used
Background assessment	1	Demographic questionnaire, psychometric battery of intellectual abilities, visual and auditory acuity		
Baseline assessment	1	Cued recall of four word lists: first two lists with number cues, second two with location cues	1–4	3 + 4
Mnemonic instruction	2	Introduction to a variant of interactive imagery, followed by individualized instruction and initial training		
Post-instruction assessment	1	Cued recall of six word lists using interactive imagery without assistance	5–10	7 + 8
Individually adaptive practice	3–7	Maximum of 36 lists (= 6 lists x 6 sessions) of adaptive practice to adjust individuals performance to a pre-fixed performance criterion, followed by six lists after reaching the performance criterion	11–52	11–52

Verbal knowledge. Two tests, *Spot-a-Word* and *Vocabulary*, formed a unit-weighted composite representing verbal knowledge. The composite was scaled to the T-metric ($M = 50$; $SD = 10$) with the total sample providing reference values. For the *Spot-a-Word* test, 35 items containing one word and four pronounceable non-words were presented successively on the screen. Participants were asked to select the word without any time pressure. Number of correct responses was the dependent variable. For the *Vocabulary* test, 16 words were presented one-by-one on the screen. Participants produced definitions for each item that were coded by two independent raters. Each response received a score of 0 (wrong), 1 (partially correct), or 2 (correct). The sum of the 16 scores was the dependent variable. Testing time was unlimited.

Paired-associates. As a marker of episodic memory we used *Paired-associates*. Eight pairs of nouns were presented twice at a rate of 5 s per pair. After each of two presentations, the first noun of each pair was presented as a recall cue. The dependent variable was the total number of correctly remembered items across the two lists, scaled to the T-metric.

Reasoning. The T-scaled unit-weighted composite representing reasoning was composed of three tasks, *Figural Analogies, Letter Series*, and *Practical Problems*. In all three tasks the test phase was terminated when subjects made three consecutive false responses, when they reached the maximum time limit (15 min), or after they had answered the last item of the test. In the *Figural Analogies* test, items followed the format "A is to B as C is to?". Participants chose one of five alternative answers to complete the open figure analogy. The number of correct responses was the dependent variable. For each item of the *Letter Series* test, a series of five letters followed by a question mark was presented. Participants had to choose the right letter out of five alternatives that logically followed the underlying rule of the letter series used in each item. The dependent variable was the number of correct responses. In the *Practical Problems* task, participants solved everyday problems, such as the hours of a bus schedule, instruction of medication as well as other forms and tables. Answers were given by choosing one of five alternatives and the dependent variable was the number of correct responses.

Perceptual speed. Two tests, *DSS* and *Digit Letter*, formed a T-scaled unit-weighted composite representing perceptual speed. For the *DSS* test, the Wechsler (1958) version of the test was used. Participants had 90 s to write as many symbols as possible. The number of correctly written symbols was the dependent variable. The *Digit Letter* test closely resembles the *DSS* test except that subjects had to name letters instead of writing symbols with respect to corresponding digits. The dependent variable was the total number of correct responses after 3 min.

Baseline assessment

In the second session, individuals were asked to encode and recall four lists of 16 words each. The first two lists involved numbers ranging from 1 to 16 as cues. The 16 locations were used for the last two lists as well as for the rest of the experiment.

Mnemonic instruction

In the next two sessions, participants were introduced to a modified interactive-imagery version of the *Method of Loci*. The first session took place in age-homogeneous groups of 3–4 individuals. After introducing the participants to the historical origins of the method, the principles of the method were explained by giving concrete examples. The instruction emphasized the generation of interactive images that associate the location cue with the to-be-learned word. Participants then practiced the technique with two word lists. Instruction and supervised training were continued individually with six word lists in the second instruction session. Supervised training included prompts to verbalize and discuss all aspects of image formation and image retrieval, collaborative image generation, assistance during recall, repetition and elaboration of instructions, as well as various other forms of encouragement.

Post-instruction assessment

In this session, and all further sessions, six lists of location-word pairs were presented sequentially for encoding and retrieval. No assistance in using the mnemonic technique was provided.

Individually adaptive practice

This phase of individual practice sessions used adaptive adjustment of encoding times (cf. Kliegl and Lindenberger, 1993) to control task difficulty individually. For each participant, this part of the study lasted between three and seven sessions, depending on the number of sessions needed to reach stable levels of memory performance as defined by the adaptive practice procedure (see below). Individuals participated in one or two sessions per week, with a minimum of 2 days between sessions.

For each individual, an adaptive algorithm determined the amount of encoding time per word for the next list by three variables: encoding time of the current list, the current step width of adjustment, and the alteration, which is a variable that indicate the direction (i.e., increased, decreased, or equal) of the previous adjustment (for details and a numerical example, see Brehmer et al., 2004). During practice, the values of all three variables were updated after each list to maximize the likelihood that a given individual would correctly recall 10 out of 16 words in the next list. When the step width for the next list was lower than 0.08 s or when six practice sessions were completed, a final session was completed. Depending upon the speed with which the adaptive practice algorithm converged, the final session was scheduled after the third to the seventh practice session. In this final session, encoding time was adjusted to fix each individual's level of performance to 50% correct and was held constant across the six lists given to participants in this session. This time-relative criterion of correct performance was chosen because of considerations for subsequent memory analyses using electroencephalography, which are not reported here. For motivational reasons, the criterion was higher (i.e., 10 out of 16 word, or 62.5% correct) during practice.

DATA ANALYSIS

The dependent variable: timed recall score

In this study, information regarding memory performance comes from both encoding times and number of correctly recalled items. Thus, both pieces of information must be taken into account. Typically, the function relating encoding time to the number of words recalled approximates a logarithmic function (e.g., Kliegl et al., 1994). Therefore, we divided the number of correctly recalled items by the log of the associated encoding time to produce a single dependent variable (henceforth, Timed Recall Score; see also Brehmer et al., 2007). We also scaled up this score by a factor of 10 to produce a variance of approximately the same magnitude as the T-scaled cognitive background composites.

Modeling instruction gains

To analyze instruction gains (i.e., the difference between baseline and post-instruction assessments; see **Table 2**) we fitted a confirmatory two-factor model to the data from the baseline assessment and the post-instruction assessment (see **Figure 1A**). That is, we assumed a latent unobserved variable representing an individual's latent error-free baseline performance score (BP) before introduction to the mnemonic technique and a latent variable representing an individual's score after instruction (Post). The latent BP score is defined as a unit-weighted factor of two observed variables [list 3 (l3) and list 4 (l4)], representing performance on the first and second lists using landmark cues in the baseline assessment (the first two lists had numbers as cues), respectively. The latent post-score is defined as a unit-weighted factor of two other observed variables (l7 and l8), representing performance on the third and fourth lists presented to participants in the post-instruction assessment. The reason for including only two lists from the post-instruction assessment was to match the list-order of the lists tapping baseline performance. We simultaneously and freely estimate the error variances (σ^2_{e3}, σ^2_{e4}, σ^2_{e7}, and σ^2_{e8}), the autocovariances between the errors ($\rho_{e3,e7}$ and $\rho_{e4,e8}$), and the mean difference between the lists used as indicators of baseline and post-instruction performance ($\mu_{listdiff}$). Of particular interest, we simultaneously estimate the mean of baseline performance (μ_{BP}), interindividual differences in baseline performance (σ_{BP}), the mean of the latent post-instruction performance (μ_{post}), interindividual differences in post-instruction performance (σ_{post}), and the correlation between baseline performance and post-instruction performance ($\rho_{BP,post}$). We also included the cognitive composites of perceptual speed, episodic memory, reasoning, and verbal knowledge as observed variables, and allowed these to freely covary among themselves and with latent baseline performance and post-instruction performance (not shown in **Figure 1A**)[1]. In order to compare the estimates across age groups, we estimated this model as a multigroup model (children, younger adults, and older adults). In the starting model, no across-group constraints were applied. With this model, we can inspect the standard deviations of the latent factors, baseline performance, and post-instruction performance, and test for the effects of training on between-person differences expected from the compensation and magnification views.

Next, we reformulated the confirmatory factor model into a latent difference model (LDM; McArdle and Nesselroade, 1994). **Figure 1B** displays a graphical representation of the LDM as we implement it here. In this model, the latent post-scores are defined as the unit-weighted sum of the latent pre-score plus a latent difference score *(Gain)*, so that the *Gain* factor is interpreted as the latent difference (reliable gain) from the baseline to the post-instruction assessment. Thus, this gain factor reflects instruction gains. This latent difference approach attenuates problems related to unreliability of raw difference scores by estimating the mean and variance of differences separately from error variance. Of particular interest, this models allows for simultaneously estimating the mean of baseline performance (μ_{BP}), interindividual differences in baseline performance (σ_{BP}), the mean of the latent gain scores (μ_{gain}), interindividual differences in gain (σ_{gain}), and the correlation between baseline performance and gain ($\rho_{BP,gain}$). Thus, with this model we can examine the prediction that magnification and compensation views have regarding the correlations between initial level of performance and gains from instruction in a methodologically rigorous manner.

Modeling practice gain

We analyzed practice gains with a latent curve model (LCM; e.g., Bryk and Raudenbush, 1987; McArdle and Epstein, 1987; Meredith and Tisak, 1990; McArdle, 2006). **Figure 2** displays a graphical representation of the LCM implemented here. The observed variables, l11–l52, emanate from the seven sessions in the phase of individually adaptive practice, each session including the presentation of six location-word lists. In a linear LCM, two latent variables, the intercept IC and the linear slope S, are proposed to account for the time series information. The linear slope S represents linear gain from practice by constraining the 42 loadings of the observed variables on S to increase linearly. The intercept IC represents an individual's latent score at the end of the time series (i.e., at l52) by setting the factor loading of the observed variable l52 on S to zero (i.e., l11 has a −41 loading on S, l12 has a −40 loading, etc.; see the loading matrix (Λ) in **Figure 2**). The intercept and the linear slope factors are estimated at the mean level (i.e., their means μ_{IC} and μ_S are estimated), they both allow for interindividual differences (i.e., their standard deviations σ_{IC} and σ_S are estimated), and they may covary $\rho_{IC,S}$. The error variance σ^2_e is commonly assumed to have a mean of zero and to neither correlate nor change over time. Estimating the six parameters mentioned so far (μ_{IC}, μ_S, σ_{IC}, σ_S, $\rho_{IC,S}$, σ^2_e) corresponds to estimating a classic linear LCM. We included an additional factor representing the orthogonal quadratic effect (S2). For these factors, preliminary analyses showed no significant interindividual differences (i.e., standard deviations) for any of the age groups. Therefore, we did only estimate the mean μ_{S2} and not the standard deviation.

In addition to the standard modeling of the time series with polynomials, we included session-wise factors representing the unique linear slope within a session. The loadings of the observed variables (six location-word lists for each of the seven sessions) on

[1]In all models applied in this paper the psychometric composites were included as a single indicator of a latent variable with a variance of one and the path (now representing the standard deviation of the cognitive composite) as well as the intercept freely estimated. The latent variable was allowed to correlate with other variables. This implementation allows for direct estimation and comparison of standardized covariances (i.e., correlations) in the models.

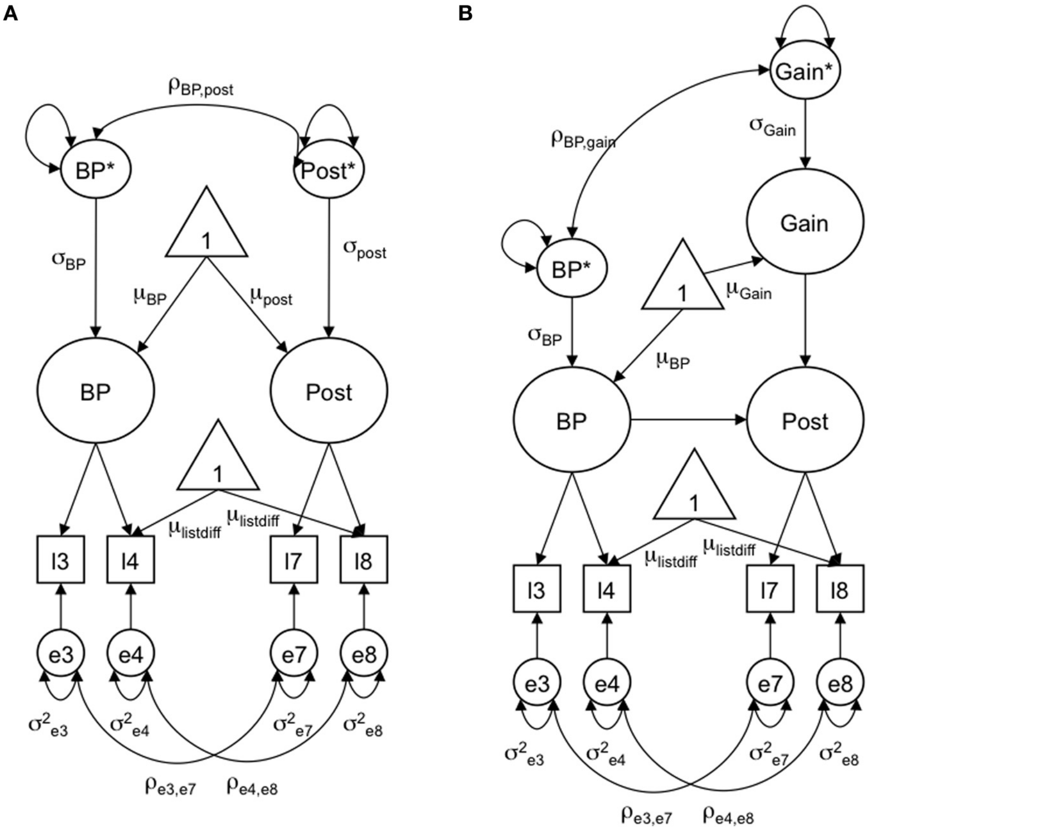


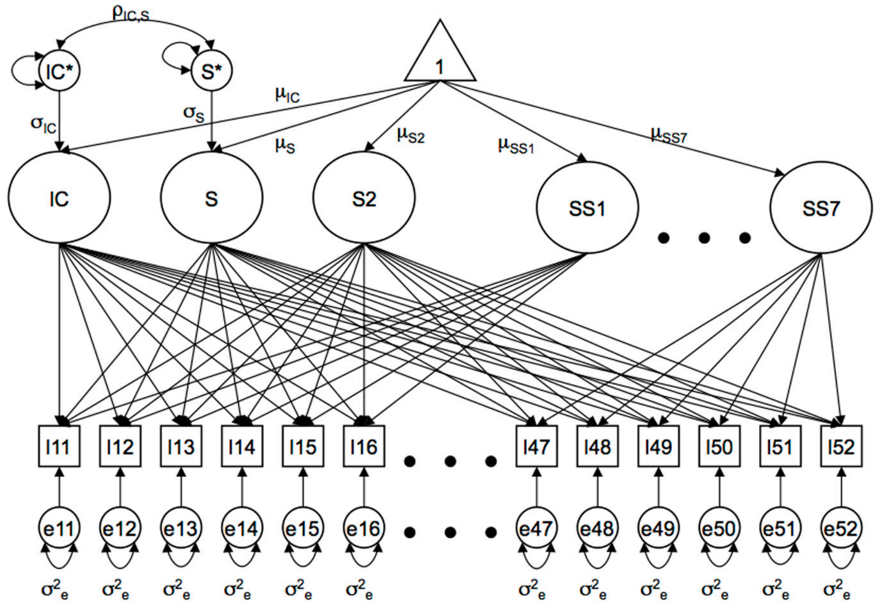
FIGURE 1 | Graphical representation of the confirmatory factors model (A) and the latent differences score model (B) used to estimate gains from mnemonic instruction (baseline plasticity). Observed variables are represented by squares, latent variables by circles, regression weights by one-headed arrows, and variances and covariances by two-headed arrows. The triangle indicates means. Unlabeled parameters are fixed to 1. BP, baseline performance; POST, post-instruction performance; I, list.

the session-wise slope factors (SS1–SS7) were defined as linearly increasing across lists within a session. The session-wise slope factors were included because we expected proactive interference from the preceding lists (e.g., Kliegl and Lindenberger, 1993) and, to some extent, other reactive effects related to list-order (e.g., fatigue) to reduce practice-related gains on performance within sessions. We freely estimated the means of the session-wise slope factors (μ_{SS1}–μ_{SS7}) but fixed their standard deviations to zero. The assumption that the session-wise reactive effects took on a linear form without interindividual differences were based on visual inspection of the data. Specifically, we averaged the *Timed Recall Score* over sessions by list position within a session for each individual. Separately for the age groups, the individual means are displayed as a function of list position in **Figure 3**, which clearly suggests an approximately linear decrease as a function of list position for most of the individuals. Furthermore, individual differences in the slopes appeared to be limited. Indeed, preliminary analyses allowing the variances for the session-wise slopes to be estimated did not result in an increase in fit, further bolstering the decisions to model these session-wise slopes without allowing for interindividual differences.

In analogy to the analyses of the instruction gains, we included the cognitive composites (not shown in **Figure 2**) as observed variables, and allowed these to freely covary among themselves as well as with the intercept and the linear slope. In addition, we estimated the model as a multigroup model (children, younger adults, and older adults). In the starting model, no across-group constraints were applied.

Handling missingness

Not all individuals contributed data to all variables. For the analyses of instruction gains with the LDM, the number of missing values was limited (a few missing values owing to technical problems and deletion of outliers). For practice gains, the number of missing values was dramatically higher, reflecting planned missingness due to the termination rule of the adaptive training procedure (see *General Procedures*; cf. McArdle, 1994). Specifically, all individuals provided scores in the first three sessions (l11–l34), but thereafter data become more and more sparse. Planned missingness was handled by taking the scores from each participant's final session and imputing these scores through the rest of the time series. This procedure assumes that the last completed session provides an accurate description of asymptotic performance, both with respect to the overall time series as well as to the session-wise reactive effects. Previous analyses suggested that a step width



Λ =

	IC	S	S2	SS1	• • •	SS7
I11	1	-41	0	-2.5	0	0
I12	1	-40	-40	-1.5	0	0
I13	1	-39	-78	-0.5	0	0
I14	1	-38	-114	0.5	0	0
I15	1	-37	-148	1.5	0	0
I16	1	-36	-180	2.5	0	0
⋮						
I47	1	-5	-180	0	0	-2.5
I48	1	-4	-148	0	0	-1.5
I49	1	-3	-114	0	0	-0.5
I50	1	-2	-78	0	0	0.5
I51	1	-1	-40	0	0	1.5
I52	1	0	0	0	0	2.5

FIGURE 2 | Graphical representation of the latent growth curve model implemented here. Observed variables are represented by squares, latent variables by circles, regression weights by one-headed arrows, and variances and covariances by two-headed arrows. The triangle indicates means. Unlabeled parameters are fixed to the values displayed in the matrix of loadings. IC, intercept, reflecting post-training performance; S, linear slope; S2, quadratic slope; SS1–7, session-wise linear slopes; I, list.

below 0.08 is conservative enough for making this assumption (Brehmer et al., 2007).

Remaining instances of missingness (due to technical problems and deletion of outliers) were accommodated by estimating the model with *Full Information Maximum Likelihood* (FIML; Finkbeiner, 1979; Arbuckle, 1996; Duncan et al., 1998; Wothke, 2000; Enders, 2001; Schafer and Graham, 2002). The FIML algorithm does not result in imputed values but uses the information in the complete data for estimating parameters that involve missing values. The FIML algorithm and related approaches generate more precise and less biased population estimates than other widespread procedures dealing with missing values (e.g., listwise deletion, regression imputation, mean imputation; e.g., Wothke, 2000; Schafer and Graham, 2002). The FIML algorithm operates under the assumption of *Missing-at-Random* (MAR; Rubin, 1976; see Schafer and Graham, 2002, for a non-technical treatment), which means that the probability that a score on variable *X* is missing may depend on other variables in the model, but not on *X* itself. Note also that under the MAR assumption a relationship between missingness and *X* produced by the mutual association to the other variables in the model is allowed, but there must be no residual relationship between missingness and *X* once the other variables are taken into account.

General statistical considerations

We note that our sample size is small for SEM. Some methodological limitations associated with small sample sizes are, for example, potential violations of multivariate normality, problems with improper solutions, and low power. To address potential violations of multivariate normality, we devoted considerable attention to the screening of variables. We detected five outliers among the post-instruction lists, seven outliers among the practice lists,

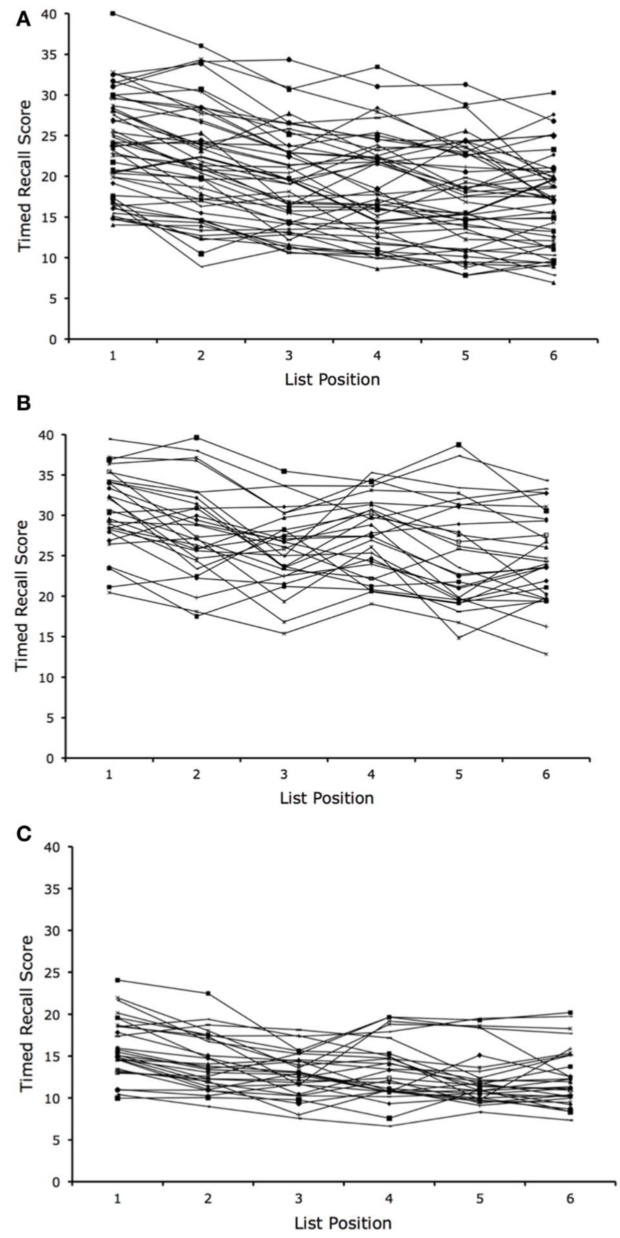


FIGURE 3 | Timed Recall Scores averaged over sessions by list position within a session for each individual in the group of children (A), younger adults (B), and older adults (C). Each line represents the scores for one individual.

one outlier for reasoning, and two outliers for perceptual speed. After deletion of the outlier scores, skewness, and kurtosis were within an acceptable range for all variables ($\text{range}_{\text{skewness}} = -2.5$ to 1.7; $\text{range}_{\text{kurtosis}} = -1.7$ to 8.3), indicating satisfactory univariate normal distributions (e.g., Kline, 1998). Satisfactory univariate distributions also reduce the risk for violations of multivariate normality. The only variable bordering to deviations from normal distribution was the second list (l8) indicating post-instruction performance for the group of younger adults (skewness $= -2.5$; kurtosis $= 8.3$), which reflected a tendency for ceiling effects. This tendency arose because encoding time was fixed across all individuals at 10 s for the baseline and post-instruction assessments. In addition to univariate screening, we visually inspected the graphed time series of each individual for atypical patterns. No individual time series was judged to constitute a multivariate outlier. In summary, we found no violations of multivariate normality in the final data set. In addition, we note that minimum was achieved without problems and no improper solutions were obtained. Finally, the power of the present statistical approach is, in the case of the LCM, boosted by the abundance of variables from which relatively few substantively important parameters are extracted (e.g., Hertzog et al., 2008). Nonetheless, the LCM applied is quite complex considering the limited sample size, and we, therefore, also did follow-up analyses applying the LDM to the analyses of practice gains (see Results for a more detailed description).

We utilized AMOS 5.0 for all computations. Model fit was evaluated with the χ^2 statistic and associated *p*-value, the normed χ^2 (χ^2/df), the *Comparative Fit Index* (CFI), and the *Root Mean Square Error of Approximation* (RMSEA). A χ^2/df below 2, a CFI above 0.90, and a RMSEA below 0.08 indicate acceptably fitting models (Arbuckle and Wothke, 1999). The likelihood ratio test (difference in χ^2; $\Delta\chi^2$) was used for comparing nested models. The level for all statistical decisions was 0.05.

RESULTS

BASELINE PERFORMANCE AND INSTRUCTION GAINS

First we estimated the confirmatory two-factor model of baseline and post-instruction performance displayed in **Figure 1A** as a multigroup model (children, younger adults, and older adults) while including the cognitive composites of perceptual speed, episodic memory, reasoning, and verbal knowledge as observed variables. This starting model had an acceptable fit, $\chi^2 = 39.46$, df $= 30$, $p = 0.116$, CFI $= 0.946$, RMSEA $= 0.055$. In this model we tested the compensation view's prediction that interindividual differences in performance decrease after instructions by comparing the starting model with a model assuming that the standard deviations of the two latent factors were equal across time for all groups. This model produced a decrease in fit, $\Delta\chi^2 = 57.52$, df $= 2$, $p < 0.001$. Fixing the standard deviation to equal across time separately for the young children, young adults, and older adults resulted in decreases in fit for all these three models in comparison with the starting model, $\Delta\chi^2 = 12.49$, df $= 1$, $p < 0.001$ for children, $\Delta\chi^2 = 34.84$, df $= 1$, $p < 0.001$ for younger adults, and $\Delta\chi^2 = 10.20$, df $= 1$, $p < 0.001$ for older adults. The standard deviations decreased after instruction for all groups.

Next we estimated the LDM of instruction gains shown in **Figure 1B**. The starting model had a fit identical to the confirmatory factor model reported above. We started by examining the compensation view's prediction that groups starting out lower would gain more from instruction. The means at baseline and post-instruction assessments (predicted from the mean gain) are displayed as a function of age group in **Figure 4**. An inspection of this figure suggests age-group differences in baseline performance. Estimating the means of baseline performance to be equal across age groups, as an omnibus test of group differences, yielded a reliably less well fitting model than the

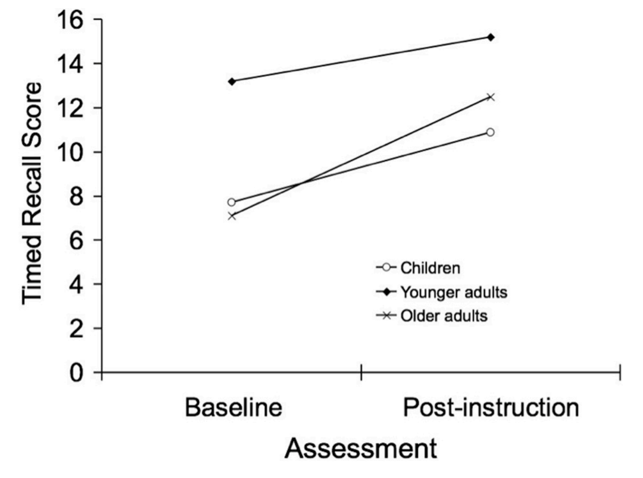


FIGURE 4 | Baseline performance and gains from instruction. Mean performance (Timed Recall Score) at baseline and post-instruction assessment for children, younger adults, and older adults, as predicted from baseline performance and instruction gain.

starting model, $\Delta\chi^2 = 40.79$, df $= 2$, $p < 0.001$. Univariate tests showed that younger adults ($\mu_{pre} = 13.25$) performed significantly better than both children ($\mu_{pre} = 7.74$), $\Delta\chi^2 = 35.53$, df $= 1$, $p < 0.001$, and older adults ($\mu_{pre} = 7.09$), $\Delta\chi^2 = 32.81$, df $= 1$, $p < 0.001$. Children and older adults did not differ significantly in baseline performance, $\Delta\chi^2 = 0.53$, df $= 1$, $p > 0.467$.

All groups gained reliably from instruction. Children gained on average 3.21 scores ($z = 6.60$), younger adults gained 1.97 scores ($z = 3.20$), and older adults gained 5.38 scores ($z = 7.22$). The omnibus test involving average gains from instruction indicated significant age-group differences, $\Delta\chi^2 = 10.93$, df $= 2$, $p < 0.004$. Univariate tests showed that the group of older adults gained significantly more than both children, $\Delta\chi^2 = 5.22$, df $= 1$, $p < 0.022$, and younger adults, $\Delta\chi^2 = 10.73$, df $= 1$, $p < 0.001$. Note, however, that there was a tendency for ceiling effects at post-instruction assessment for the younger adults, which probably reduced the mean gains for this group.

Next we addressed the predicted negative correlation between baseline performance and gains from instruction. All variances and standard deviations were significant. **Figure 5** displays individual baseline and post-instruction performances (average of the two lists at each assessment) separately for the children (a), younger adults (b), and older adults (c). An inspection of **Figure 5** reveals pronounced between-person differences in instruction gains: within age groups, individuals differed in how much they gained in memory performance from mnemonic instruction. **Table 3** displays the correlations among baseline memory performance, gains from mnemonic instruction, and the cognitive composites, separately for the three age groups. The most salient finding reported in **Table 3** is the strong negative correlations between baseline performance and instruction gain observed in all age groups, indicating that individuals entering the study with low memory performance gained more from instruction than those who entered the study with good memory performance (see also **Figure 5**). Caution is, however, warranted when interpreting this finding for the group of younger adults because their tendency for a ceiling effect at post-instruction assessment may contribute to the negative correlation. Likewise, correlations between the cognitive composites and instruction gain indicated that *Paired-associates* performance was negatively related to instruction gain in the two adult groups.

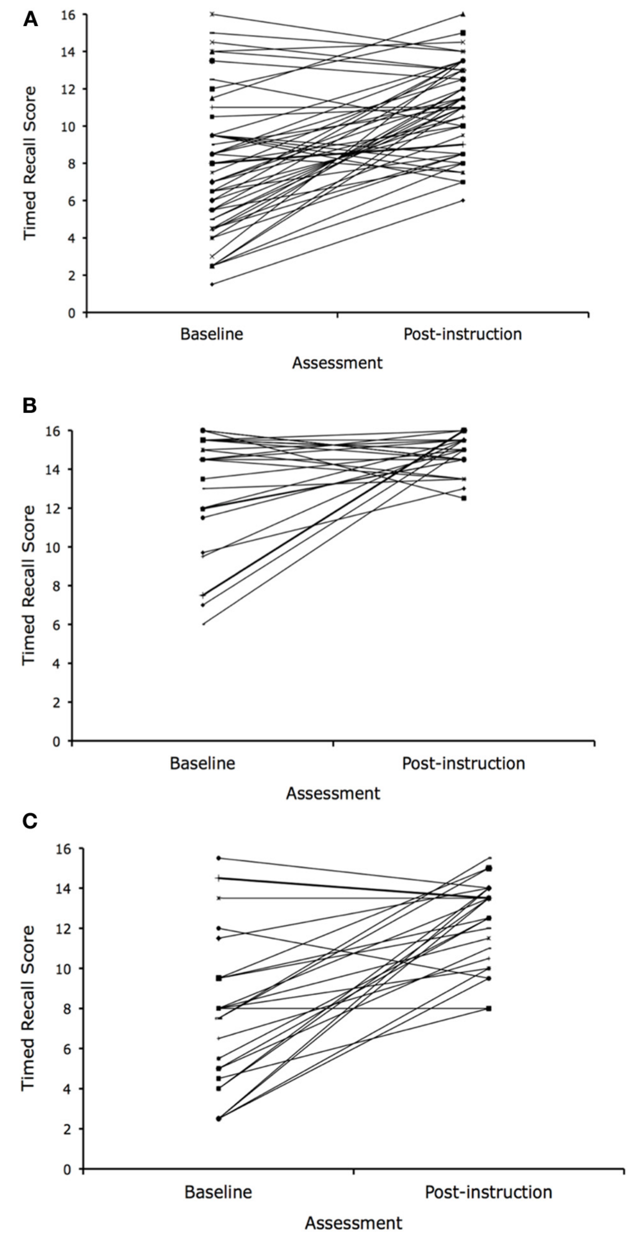


FIGURE 5 | Individual baseline performance and gains from instruction. Performance at baseline and post-instruction assessments for each individual in the group of children **(A)**, younger adults **(B)**, and older adults **(C)**. The scores at baseline and post-instruction assessments are unit-weighted composites of the two lists indicating performance at each assessment, respectively. To plot all scores on the positive axis, a constant of 10 has been added to all scores.

Table 3 | Correlations among cognitive composites, baseline memory performance, and gain in memory performance from baseline to post-instruction assessments (instruction gain) separately for the age groups.

	Instruction gain	Paired-associates	Perceptual speed	Reasoning	Verbal knowledge
CHILDREN					
Baseline performance	−0.85*	0.35*	0.00	0.22	0.24
Instruction gain	—	0.01	0.29	−0.23	0.10
YOUNGER ADULTS					
Baseline performance	−0.99*	0.39*	0.15	0.11	−0.02
Instruction gain	—	−0.37*	−0.15	−0.04	0.06
OLDER ADULTS					
Baseline performance	−0.90*	0.66*	0.20	0.44*	0.11
Instruction gain	—	−0.56*	−0.01	−0.19	0.10

*Note: Perceptual speed = Unit-weighted composite of Digit Symbol Substitution (Wechsler, 1958) and Digit Letter; Reasoning = Unit-weighted composite of Figural Analogies, Letter Series, and Practical Problems; Verbal Knowledge = Unit-weighted composite of Spot-a-Word and Vocabulary. *p < 0.05.*

To sum up, the analyses of instruction gains reveal an empirical pattern consistent with the compensation account: interindividual differences in memory performance are reduced after instructions, group mean differences are reduced, and baseline performance correlates negatively with gains from instructions within the groups.

BASELINE PERFORMANCE AND PRACTICE GAINS

To address the predictions regarding practice gains, we simultaneously estimated the LDM of instruction gains and a LCM of the practice gains. This model was estimated as a multi-group model (children, younger adults, and older adults) while allowing the cognitive composites to freely covary among themselves and with baseline performance, instruction gain, linear practice gain, and post-training performance. The starting model estimated 171 parameters with a log-likelihood function[2] of 21,750.47.

We first tested the magnification view's prediction that interindividual differences in performance increase from training by comparing the starting model with a model assuming that the standard deviations of the baseline assessment and post-practice performance were equal across time for all groups. This model produced a decrease in fit, $\Delta\chi^2 = 57.88$, df $= 3$, $p < 0.001$. The standard deviations increased from baseline assessment to post-practice assessment for the groups of children (3.39–8.23), $\Delta\chi^2 = 33.31$, df $= 1$, $p < 0.001$, and younger adults (2.83–8.22), $\Delta\chi^2 = 24.52$, df $= 1$, $p < 0.001$, but not for the group of older adults (3.53–3.69), $\Delta\chi^2 = 0.05$, df $= 1$, $p > 0.816$.

Next, we examined the means predicted from the estimates of the intercept, linear slope, and quadratic slope of the practice period (see **Figure 6**). All groups gained in memory performance from practicing. Children had a linear mean gain (μ_S) of 0.17 ($z = 8.31$), younger adults gained 0.35 scores ($z = 10.32$), and older adults gained 0.04 scores ($z = 3.70$) per practiced list. The omnibus test indicated significant age-group differences, $\Delta\chi^2 = 52.51$, df $= 2$, $p < 0.001$. Pairwise comparisons showed that younger adults gained significantly more than children, $\Delta\chi^2 = 17.37$, df $= 1$, $p < 0.001$. In turn, children gained more than older adults, $\Delta\chi^2 = 21.16$, df $= 1$, $p < 0.001$.

Figure 6 suggests that the practice-related improvements in memory performance took on a quadratic shape for children and younger adults. In fact, the quadratic mean slope (μ_S) was significant for children (−0.004; $z = 4.62$) and younger adults only (−0.015; $z = 9.35$). Note that follow up analyses showed that the

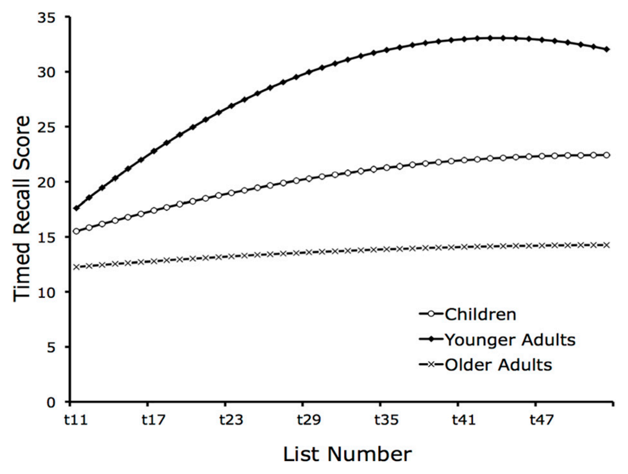


FIGURE 6 | Practice gains. Mean performance (Timed Recall Score) during the practice phase as predicted from the parameter estimates of the intercept, linear slope, and quadratic slope as a function of list number and age group.

[2]With FIML, the overall log-likelihood fitting function for a model is the sum of the casewise likelihoods. The chi-square statistic and derivate indices are calculated from the difference between the log-likelihood fitting functions of the saturated (unrestricted) model and the restricted model (e.g., the applied LCM) with the degrees of freedom equal to the difference in the number of estimated parameters between the models. This calculation was done for the LDM applied to the instruction gains. However, not enough information was available in the data set to fit the saturated model for the LCM. Thus, we report only the minimum value of the function of log-likelihood for the restricted model (i.e., the applied LCM). The lack of the conventional fit indices for the LCM is not problematic because the fit of the model is not critical *per se*; rather, the major focus is on the parameter estimates, differences in the estimates across age groups, and thus differences between alternative models.

apparent tendency for declining performance for younger adults toward the end of the time series could be partially removed by adding a cubic trend. However, this trend did not reach significance ($p > 0.13$) and we thus decided against including it in the final models.

Finally, we addressed the predicted positive correlation between baseline performance and gains from practice. Importantly, all estimated variances and standard deviations, including the linear practice gains, were statistically reliable. **Table 4** displays the correlations among post-training memory performance, practice gain, and the cognitive ability composites. The most salient finding is the uniformly strong and positive correlations between post-training performance and practice gains, indicating that the magnitude of practice-related gains for an individual was strongly determining the individual's rank order at the end of training. All cognitive composites showed some significant and positive associations with post-practice performance and with linear practice gains, but it is difficult to discern any consistent and salient pattern within or across age groups for these correlations.

Table 5 presents the correlations, separately for the three age groups, among all the estimated components of the training curve. The new information in this table is a weak pattern of positive correlations between baseline performance and post-practice performance. In addition, for children, baseline performance correlates positively with practice gains.

Because the main take-home messages from these analyses are based on a quite complex model fitted to a relatively small sample, we also double-checked these results in a simplified model of practice gains. In this model, fitted as a multigroup model (children, younger adults, and older adults), the practice gains were modeled in a similar way as the instruction gains, with a latent-difference score model. For the practice gains, a pre-practice factor was formed by the six first lists of the practice phase and a post-practice factor was formed by the last six lists completed by each participant. Initial analyses of these factors confirmed that

Table 4 | Correlations among cognitive composites, post-training memory performance (IC), and linear gain in memory performance from practice (S) separately for the age groups.

	Practice gain (S)	Paired-associates	Perceptual speed	Reasoning	Verbal knowledge
CHILDREN					
Post-training (IC)	0.87*	0.38*	0.40*	0.23	0.40*
Practice gain (S)	—	0.12	0.42*	0.05	0.18
YOUNGER ADULTS					
Post-training (IC)	0.91*	0.20	0.14	0.34*	0.28
Practice gain (S)	—	0.13	0.02	0.33	0.22
OLDER ADULTS					
Post-training (IC)	0.76*	0.19	0.29	0.54*	0.31
Practice gain (S)	—	−0.16	0.03	0.23	0.11

*Note: Perceptual speed = Unit-weighted composite of Digit Symbol Substitution (Wechsler, 1958) and Digit Letter; Reasoning = Unit-weighted composite of Figural Analogies, Letter Series, and Practical Problems; Verbal Knowledge = Unit-weighted composite of Spot-a-Word and Vocabulary. *p < 0.05.*

Table 5 | Correlations among baseline memory performance, instruction gain, gain from practicing (S), and post-training performance (IC) separately for the age groups.

	Baseline performance	Instruction gain	Practice gain (S)	Post-training (IC)
CHILDREN				
Baseline performance	—			
Instruction gain	−0.85*	—		
Practice gain (S)	0.33*	−0.05	—	
Post-training (IC)	0.46*	−0.05	0.87*	—
YOUNGER ADULTS				
Baseline performance	—			
Instruction gain	−0.99*	—		
Practice gain (S)	−0.02	0.13	—	
Post-training (IC)	0.11	0.03	0.98*	—
OLDER ADULTS				
Baseline performance	—			
Instruction gain	−0.90*	—		
Practice gain (S)	−0.09	0.18	—	
Post-training (IC)	0.31	0.02	0.76*	—

*Note: *p < 0.05.*

within-group interindividual differences increased for children and younger adults. That is, the standard deviations increased from baseline assessment to post-practice assessment for the groups of children, $\Delta\chi^2 = 22.09$, df $= 1$, $p < 0.001$, and younger adults, $\Delta\chi^2 = 19.91$, df $= 1$, $p < 0.001$. When these factors were reformulated as latent-difference score model, we could confirm that younger adults increased on average more in memory performance than children, $\Delta\chi^2 = 13.47$, df $= 1$, $p < 0.001$ and that children increased more than older adults, $\Delta\chi^2 = 12.89$, df $= 1$, $p < 0.001$. Finally, the correlation between baseline performance and practice gains was significant in the group of children, $r = 0.53$, $p = 0.010$.

In summary, the main message from these analyses are that practice-related changes in memory performance partly follows a pattern consistent with the predictions from the magnification model: relative to baseline performance, age-group differences increased after practice; for children and younger adults, within-group interindividual differences increased after practice; and in children, baseline performance as well as cognitive abilities assessed before the intervention tended to be positively associated with practice gains.

DISCUSSION

This article reports that between-person differences in associative memory performance are reduced after mnemonic instructions and that baseline performance within age groups correlates negatively with instruction gains. In contrast, age-group differences, and between-person differences among children and younger adults, increase as a function of extended adaptive practicing, and baseline performance and cognitive abilities tends to be weekly positively associated with practice gains for the group of children. Thus, the compensation view fit the pattern of instruction gains nicely, while the magnification model fit the interindividual differences in practice gains better than the compensation model.

Clearly, the present results are consistent with the distinction between flexibility and plasticity (Lövdén et al., 2010). Flexibility, in our view, denotes the capacity to optimize the brain's performance within current structural constraints, using the available range of existing representational states. In contrast to flexibility, plasticity denotes the capacity for changes in the possible range of cognitive performance enabled by flexibility. Instruction gains may be primarily acquired through flexibility, and if the brain's functioning is already appropriate for handling the task at hand, then little can be gained by altering the way a particular task is executed, and thus better performing individual will gain less. In contrast, gains primarily acquired through adaptive practice may reflect plasticity and extend the possible range of performance, possibly by boosting associative potential (Brehmer et al., 2007; Shing et al., 2008, 2010). Initial performance should then correlate with individual differences in plasticity because initial performance can be viewed as a reflection of past manifestations of plasticity.

These theoretical notions also help to explain why older adults gained more from instructions than children, whereas children gained more from practicing than older adults, despite the fact that both groups were performing similarly at baseline and on measures of fluid cognitive ability (see also Brehmer et al., 2007). Specifically, older adults may, perhaps due to their larger knowledge base, possess better possibilities to rapidly shift to a more effective mnemonic strategy, while children may possess a more plastic associative memory system (Werkle-Bergner et al., 2006; Shing et al., 2008, 2010).

This study has several benefits. One positive characteristic of the study is the lifespan sample, which gave us the opportunity to examine the validity of the magnification and compensation views across the lifespan and for both instructions and practice gains. Another advantage is the inclusion of an extensive training program using an adaptive procedure to encompass the wide measurement space. The adaptive procedure also ensured that all participants faced equally demanding conditions during training, thus minimizing confounding between-person differences in the impetus for change in performance (Lövdén et al., 2010). Finally, our use of modern statistical procedures appropriate for the explicit estimation of change provides an important addition to past research in this area and circumvents several of the methodological problems discussed in the psychometric literature on relations between initial performance and subsequent change (Jin, 1992). These methodological improvements gave us the opportunity to, in a rigorous manner, extend the evaluation of the magnification and compensation models to interindividual differences.

A number of limitations should be noted as well. First, generalization from the specific context in which this study was conducted to other forms of training is not straightforward. In particular, the present target task of training deviates somewhat from past studies on memory plasticity with the method of loci (e.g., Kliegl et al., 1990; Lindenberger et al., 1992; Kliegl and Lindenberger, 1993). In the present task, location cues were not presented in a fixed serial order but randomized at each list. Hence, the current task was less strategic but loaded more on the associative component of episodic memory (e.g., Shing et al., 2010). It is possible that this feature enhanced the compensatory pattern found for baseline plasticity. Specifically, encoding and retrieval strategies such as imagery might be relatively standard ways of dealing with to-be-learned materials whereas full application of the method of loci mnemonic may not. Thus, a subset of participants in this study may have applied some form of interactive-imagery strategy at baseline (cf. Dunlosky et al., 2005). Another issue is the ceiling effect of younger adults in the post-instruction session. Although we can interpret young adults' baseline performance, practice gains, and overall training gains, this ceiling effect renders it impossible to interpret younger adults' gains from instructions.

We also note that the key dependent variable was a composite score of presentation time and the number of correctly recalled items. The underlying assumption of this Timed Recall Score is that a reduction in processing time increases the effort for the participant to form a quick and effective association and that this mechanism is functionally equivalent across age groups. Previous age-comparative memory research in the field of cognitive aging supports these assumptions (Kliegl and Lindenberger, 1993; Kliegl et al., 1994), and lifespan comparisons in the domains of working memory and inductive reasoning have successfully used similar procedures (Mayr et al., 1996). Nevertheless, further methodological work on the issue of age equivalence of the Timed Recall Score is desirable. It should also be noted that our overall sample is positively selected (see Brehmer et al., 2007 for details), limiting generalizability to lower performing segments of the population. Finally, and most importantly, we note that the sample size was relatively small, especially considering the complex latent-growth curve approach to analyzing practice gains. Though follow-up analyses applying the less complex latent difference score model to this data delivered results that confirmed the main analyses, we acknowledge that the statistical power for addressing these research questions is limited. Due to this fact, we run a higher risk than usual of missing important effects and of reporting false alarms. In addition, we note that the procedure of imputing data missing due to the termination rule of the adaptive training procedure assumes that the last completed session provides an accurate description of asymptotic performance. The validity of this assumption is unknown. There is, therefore, a risk that the true shape of the mean practice gains looks different than the one we reported in **Figure 6**. Nevertheless, the main conclusion concerning the individual differences in practice gains remains valid regardless of the true shape of this learning process. This has been shown by the follow-up analyses, which only relies on the difference between initial and final performance of the practice phase. Overall, considering these limitations, future studies must confirm the present results before strong claims based on these results can be made.

Despite these limitations, the findings of this study suggest a resolution to the long-standing debate on the presence, direction, and meaning of aptitude by treatment interactions. In line with the conceptual distinction between flexibility and plasticity, we found that mnemonic instructions have compensatory effects, whereas subsequent practice magnifies between-person differences in memory performance. Future research needs to examine whether the explanatory framework introduced in this article is also helpful to interpret results from other data set with larger samples and whether it also helps to clarify the relation among initial performance, cognitive resources, and performance gains in cognitive domains other than memory. With educational issues in mind, it is clear that understanding the mechanisms that reduce and magnify between-person differences in performance is important, and may have practical and societal implications.

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REFERENCES

Arbuckle, J. L. (1996). "Full information estimation in the presence of incomplete data," in *Advanced Structural Equation Modeling,* eds G. A. Marcoulides and R. E. Schumacker (Mahwah, NJ: Erlbaum), 243–277.

Arbuckle, J. L., and Wothke, W. (1999). *Amos 4.0 User's Guide.* Chicago: Small Waters Corporation.

Baltes, P. B. (1987). Theoretical propositions of life-span developmental psychology: on the dynamics between growth and decline. *Dev. Psychol.* 23, 611–626.

Baltes, P. B., Lindenberger, U., and Staudinger, U. M. (2006). "Lifespan theory in developmental psychology," in *Handbook of Child Psychology: Vol. 1. Theoretical Models of Human Development,* 6th edn., eds W. Damon and R. M. Lerner (New York, NY: Wiley), 569–664.

Bjorklund, D. F., and Douglas, R. N. (1997). "The development of memory strategies," in *The Development of Memory in Childhood,* eds N. Cowan and C. Hulme (Sussex, UK: Psychology Press), 201–246.

Bjorklund, D. F., Miller, P. H., Coyle, T. R., and Slawinski, J. L. (1997). Instructing children to use memory strategies: evidence of utilization deficiencies in memory training studies. *Dev. Rev.* 17, 411–441.

Bower, G. H. (1970). Analysis of a mnemonic device. *Am. Sci.* 58, 496–510.

Brehmer, Y., Li, S.-C., Mueller, V., von Oertzen, T., and Lindenberger, U. (2007). Memory plasticity across the life span: uncovering children's latent potential. *Dev. Psychol.* 43, 465–478.

Brehmer, Y., Li, S.-C., Straube, B., Stoll, G., von Oertzen, T., Mueller, V., and Lindenberger, U. (2008). Comparing memory skill maintenance across the life span: preservation in adults, increase in children. *Psychol. Aging* 23, 227–238.

Brehmer, Y., Stoll, G., Bergner, S., Benoit, R., von Oertzen, T., and Lindenberger, U. (2004). *Selection of Unambiguous Visual Words, Appropriate for Children in Age-Comparable Memory Experiments: Results of a Pilot Study*. Available: http://psydoc.sulb.uni-saarland.de/volltexte/2004/189

Bryk, A. S., and Raudenbush, S. W. (1987). Application of hierarchical linear models to assessing change. *Psychol. Bull.* 101, 147–158.

Cox, B. D. (2001). Children's use of mnemonic strategies: variability in response to metamemory training. *J. Genet. Psychol.* 155, 423–442.

Cronbach, L. J. (1957). The two disciplines of scientific psychology. *Am. Psychol.* 12, 671–684.

Duncan, T. E., Duncan, S. C., and Li, F. (1998). A comparison of model- and multiple imputation-based approaches to longitudinal analyses with partial missingness. *Struct. Equ. Model.* 5, 1–21.

Dunlosky, J., Hertzog, C., and Powell-Moman, A. (2005). The contribution of mediator-based deficiencies to age differences in associative learning. *Dev. Psychol.* 41, 389–400.

Enders, C. K. (2001). The impact of non-normality of full information maximum-likelihood estimation for structural equation models with missing data. *Psychol. Methods* 6, 352–370.

Ferguson, G. A. (1956). On transfer and the abilities of man. *Can. J. Psychol.* 10, 121–131.

Finkbeiner, C. (1979). Estimation for the multiple factor model when data are missing. *Psychometrika* 44, 409–420.

Garlick, D. (2002). Understanding the nature of the general factors of intelligence: the role of individual differences in neural plasticity as an explanatory mechanism. *Psychol. Rev.* 109, 116–136.

Gaultney, J. F., Bjorklund, D. F., and Goldstein, D. (1996). To be young, gifted, and strategic: advantages for memory performance. *J. Exp. Child Psychol.* 61, 43–66.

Hertzog, C., von Oertzen, T., Ghisletta, P., and Lindenberger, U. (2008). Evaluating the power of latent growth curve models to detect individual differences in change. *Struct. Equ. Model.* 15, 541–563.

Jin, P. (1992). Toward a reconceptualization of the law of initial value. *Psychol. Bull.* 111, 176–184.

Kliegl, R., and Lindenberger, U. (1993). Modeling intrusions and correct recall in episodic memory: adult age differences in encoding of list context. *J. Exp. Psychol. Learn. Mem. Cogn.* 19, 617–637.

Kliegl, R., Mayr, U., and Krampe, R. T. (1994). Time-accuracy functions of determining process and person differences: an application to cognitive aging. *Cognit. Psychol.* 26, 134–164.

Kliegl, R., Smith, J., and Baltes, P. B. (1990). On the locus and process of magnification of age differences during mnemonic training. *Dev. Psychol.* 26, 894–904.

Kline, R. B. (1998). *Structural Equation Modeling*. New York, NY: Guilford Press.

Kramer, A. F., and Willis, S. L. (2002). Enhancing the cognitive vitality of older adults. *Curr. Dir. Psychol. Sci.* 11, 173–177.

Kwon, Y.-J., and Lawson, A. E. (2000). Linking brain growth with the development of scientific reasoning ability and conceptual change during adolescence. *J. Res. Sci. Teach.* 37, 44–62.

Li, S.-C., Lindenberger, U., Hommel, B., Aschersleben, G., Prinz, W., and Baltes, P. B. (2004). Transformation in the coupling among intellectual abilities and constituent cognitive processes across the life span. *Psychol. Sci.* 15, 155–163.

Lindenberger, U., Kliegl, R., and Baltes, P. B. (1992). Professional expertise does not eliminate age differences in imagery-based memory performance during adulthood. *Psychol. Aging* 7, 585–593.

Lindenberger, U., Mayr, U., and Kliegl, R. (1993). Speed and intelligence in old age. *Psychol. Aging* 8, 207–220.

Lövdén, M., Ghisletta, P., and Lindenberger, U. (2004). Cognition in the Berlin aging study (BASE): the first 10 years. *Aging Neuropsychol. Cogn.* 11, 104–133.

Lövdén, M., Bäckman, L., and Lindenberger, U., Schäfer, S., and Schmiedek, F. (2010). A theoretical framework for the study of adult cognitive plasticity. *Psychol. Bull.* 4, 659–676.

Mayr, U., Kliegl, R., and Krampe, R. (1996). Sequential and coordinative processing dynamics in figural transformations across the life span. *Cognition* 59, 61–90.

McArdle, J. J. (1994). Structural factor analysis experiments with incomplete data. *Multivariate Behav. Res.* 29, 409–454.

McArdle, J. J. (2006). "Dynamic structural equation modeling in longitudinal experimental studies," in *Longitudinal Models in the Behavioural and Related Sciences,* eds Kees van Montfort, Han Oud, and Alberto Satorra (Mahwah, NJ: Erlbaum, EAM Book Series), 159–187.

McArdle, J. J., and Epstein, D. (1987). Latent growth curves within developmental structural equation models. *Child Dev.* 58, 110–133.

McArdle, J. J., and Nesselroade, J. R. (1994). "Using multivariate data to structure development change," in *Life-Span Developmental Psychology: Methodological Contributions,* eds S. H. Cohen and H. W. Reese (Hillsdale, NJ: LEA), 223–268.

Meredith, W., and Tisak, J. (1990). Latent curve analysis. *Psychometrika* 55, 107–122.

Neisser, U., Boodoo, G., Bouchard, T. J., Boykin, A. W., Brody, N., Ceci, S. J., Halpern, D. F., Loechlin, J. C., Perloff, R., Sternberg, R. J., and Urbina, S. (1996). Intelligence: knowns and unknowns. *Am. Psychol.* 51, 77–101.

Rönnlund, M., Nyberg, L., Bäckman, L., and Nilsson, L.-G. (2005). Stability, growth, and decline in adult life span development of declarative memory: cross-sectional and longitudinal data from a population-based study. *Psychol. Aging* 20, 3–18.

Rubin, D. B. (1976). Interference and missing data. *Biometrika* 63, 467–474.

Schafer, J. L., and Graham, J. W. (2002). Missing data: our view of the state of the art. *Psychol. Methods* 7, 147–177.

Schaie, K. W. (1996). *Intellectual Development in Adulthood: The Seattle Longitudinal Study*. New York, NY: Cambridge University Press.

Schneider, W. (2012). "Memory development in childhood" in *Blackwell Handbook of Childhood Cognitive Development,* ed U. Goswami (London, UK: Blackwell), 236–256.

Shing, Y. L., Werkle-Bergner, M., Brehmer, Y., Muller, V., Li, S. C., and Lindenberger, U. (2010). Episodic memory across the lifespan: the contributions of associative and strategic components. *Neurosci. Biobehav. Rev.* 34, 1080–1091.

Shing, Y. L., Werkle-Bergner, M., Li, S.-C., and Lindenberger, U. (2008). Associative and strategic components of episodic memory: a lifespan dissociation. *J. Exp. Psychol. Gen.* 137, 495–513.

Sternberg, R. J., and Detterman, D. K. (eds). (1986). *What Is Intelligence? Contemporary Viewpoints on Its Nature and Definition*. Norwood, NJ: Ablex.

Sullivan, A. M. (1964). *The Relation Between Intelligence and Transfer*. Unpublished doctoral dissertation. McGill University, Montreal, QC: Canada.

Verhaeghen, P., and Kliegl, R. (2000). The effects of learning a new algorithm on asymptotic accuracy and execution speed in old age: a reanalysis. *Psychol. Aging* 15, 648–656.

Verhaeghen, P., and Marcoen, A. (1996). On the mechanisms of plasticity in young and older adults after instruction in the method of loci: evidence for an amplification model. *Psychol. Aging* 11, 164–178.

Verhaeghen, P., Marcoen, A., and Goossens, L. (1992). Improving memory performance in the aged through mnemonic training: a meta-analytic study. *Psychol. Aging* 7, 242–251.

Wechsler, D. (1958). *The Measurement and Appraisal of Adult Intelligence,* 4th edn. Baltimore, MD: Williams and Wilkins.

Werkle-Bergner, M., Müller, V., Li, S.-C., and Lindenberger, U. (2006). Cortical EEG correlates of successful memory encoding: implications for lifespan comparisons. *Neurosci. Biobehav. Rev.* 30, 839–854.

Will, B., Dalrymple-Alford, J., Wolff, M., and Cassel, J. C. (2008). The concept of brain plasticity—Paillard's systemic analysis and emphasis on structure and function (followed by the translation of a seminal paper by Paillard on plasticity). *Behav. Brain Res.* 192, 2–7.

Wothke, W. (2000). "Longitudinal and multi-group modeling with missing data," in *Modeling Longitudinal and Multilevel Data: Practical Issues, Applied Approaches, and Specific Examples,* eds T. D. Little, K. U. Schnabel, and J. Baumert (Mahwah, NJ: Erlbaum), 219–240.

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Examining neural correlates of skill acquisition in a complex videogame training program

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Acquisition of complex skills is a universal feature of human behavior that has been conceptualized as a process that starts with intense resource dependency, requires effortful cognitive control, and ends in relative automaticity on the multi-faceted task. The present study examined the effects of different theoretically based training strategies on cortical recruitment during acquisition of complex video game skills. Seventy-five participants were recruited and assigned to one of three training groups: (1) Fixed Emphasis Training (FET), in which participants practiced the game, (2) Hybrid Variable-Priority Training (HVT), in which participants practiced using a combination of part-task training and variable priority training, or (3) a Control group that received limited game play. After 30 h of training, game data indicated a significant advantage for the two training groups relative to the control group. The HVT group demonstrated enhanced benefits of training, as indexed by an improvement in overall game score and a reduction in cortical recruitment post-training. Specifically, while both groups demonstrated a significant reduction of activation in attentional control areas, namely the right middle frontal gyrus, right superior frontal gyrus, and the ventral medial prefrontal cortex, participants in the control group continued to engage these areas post-training, suggesting a sustained reliance on attentional regions during challenging task demands. The HVT group showed a further reduction in neural resources post-training compared to the FET group in these cognitive control regions, along with reduced activation in the motor and sensory cortices and the posteromedial cortex. Findings suggest that training, specifically one that emphasizes cognitive flexibility can reduce the attentional demands of a complex cognitive task, along with reduced reliance on the motor network.

Keywords: skill acquisition, training strategies, attentional control, functional MRI

INTRODUCTION

The ability of humans to acquire both simple and complex skills is a universal feature of human behavior, one that starts early in life (Piaget, 1954) and enables the development of a repertoire of cognitive, motor, and perceptual processes essential for successful human functioning. The study of skill acquisition has been the focus of research for many decades now, with many theorists proposing that skill acquisition involves an ordered series of stages, with earlier stages focused on effortful, controlled processing, characterized by greater cognitive and executive control, and later stages resulting in automaticity of behavior, depending on fewer resources and little effort (Fitts and Posner, 1967; Schneider and Shiffrin, 1977; Ackerman, 1988). An important variable in the learning of complex skills is the differential influence of training strategies on learning rate, with more efficient training regimes characterized both by a faster acquisition of the skill involved, and by a resourceful utilization of the various skill dimensions, resulting in efficient performance. The Learning Strategies Initiative (Donchin et al., 1989) outlined a series of training strategies that were examined for their ability to enhance complex skill acquisition, as implemented in a multi-faceted videogame, Space Fortress (SF). Training strategies included repeated practice on the entire task (Fixed Emphasis Training, FET), which has been the predominant mode of training and cognitive rehabilitation across various clinical populations (e.g., Chiaravalloti et al., 2005; Erickson et al., 2007), part-task training, involving principled decomposition of the complex videogame into skill and knowledge components and training individuals on the sub-parts rather than on the integrated game (Frederiksen and White, 1989), and whole-task training with variable priority (Variable Priority Training, VPT), involving training on the integrated complex task, with changing emphasis on the sub-components of the game throughout training (Gopher et al., 1989; see Fabiani et al., 1989, for a comparison of these training regimes).

The recent resurgence of interest in cognitive training to enhance cognitive vitality and neural plasticity (Boot et al., 2011; Slagter et al., 2011) has led to a re-examination of the prophylaxis offered by various training strategies for the faster acquisition of complex skills (Basak et al., 2008; Boot et al., 2010; Lee et al., 2012), cortical reorganization as evidenced by altered brain activity and connectivity (Kantak et al., 2010; Maclin et al., 2011; Voss et al., 2011), and transfer to novel tasks (Boot et al., 2010; Stern et al., 2011; Lee et al., 2012). Prioritizing different aspects of a complex task, while performing the integrated task (VPT), has been found to be beneficial for dual-task performance (Kramer et al., 1995, 1999; Bherer et al., 2008), faster learning and higher level of mastery on the videogame SF (Fabiani et al., 1989; Boot et al., 2010), and better working memory performance in older adults (Stern et al., 2011).

Adding to the behavioral literature have been recent investigations of the neural correlates of variable priority versus FET (Kantak et al., 2010; Voss et al., 2011). Employing repetitive transcranial magnetic stimulation (rTMS), Kantak et al. (2010) provided evidence for the dependence of the two practice regimes on separable cortical areas for motor memory consolidation. While application of rTMS on the dorsolateral prefrontal cortex post-variable practice resulted in attenuation of motor skill retention, it was interference with the primary motor cortices following constant practice that attenuated motor retention, thus providing evidence for the use of different cortical regions in consolidation based on the strategy implemented. Similarly, Voss et al. (2011) suggested the differential interaction of the declarative and procedural learning systems with higher-order attentional networks as a function of training strategies. After 20 h of training, the basal ganglia, associated with the learning system related to FET, and the medial temporal lobes (MTL) associated with the learning system related to VPT, both showed enhanced interaction with the fronto-parietal system. The interaction between the MTL and the fronto-parietal system in the VPT group is implicated in the increased capacity of working memory and attention (Craik et al., 1996; Olesen et al., 2004). Therefore, VPT trainees may be more efficiently utilizing their attentional network, suggesting that this training strategy involves more flexible attentional control. In addition, unique to FET, Voss et al. (2011) observed enhanced interactions between the MTL and the fronto-executive system. Given the increased interaction of the basal ganglia with the fronto-parietal system and the MTL with the fronto-executive system in the FET group, it appears that FET participants were concurrently utilizing two different cognitive control systems. The authors postulated this enhanced functional connectivity in the two attention systems to be indicative of a higher cognitive load for FET, which in turn, leads to a reliance on basal ganglia and procedural motor sequences to accomplish game performance. This unique pattern of functional connectivity in the attentional network of the FET group was thus indicative of increased engagement of attentional resources during game-play, which, relative to VPT, suggested an inefficient modulation of neural activity in attentional areas.

Research studies investigating the neurophysiological indices of skill acquisition as a function of training strategy also provide evidence for a greater increase in alpha frequency in the part-task training groups relative to the whole-task training group, providing evidence of attenuation of cognitive effort and attentional demands with an efficient training strategy (Smith et al., 1999). Recently, Maclin et al. (2011) also reported a decrease in P3 amplitude following training on the SF game for some components of the game. The investigators interpreted these results as providing evidence of greater allocation of attention to a secondary task post-training. Thus, evidence from behavioral, and neuroimaging studies provide consistent data on the superiority of training regimes that focus either on training different components of the task independently, or training that prioritizes selective aspects of a complex task within the context of the whole task during skill acquisition. In the present study, capitalizing on the benefits of part-task training and emphasis change training approaches, we examined the efficacy of a Hybrid Variable-Priority Training (HVT) approach to produce greater skill mastery (Gopher et al., 1994; Lee et al., 2012).

By combining both part-task training, which enables the breakdown of a complex task into small sub-component tasks which can then be individually mastered, and VPT, which enables participants to explore and learn new strategies and transfer sub-components skills learned during part-task training to the integrated whole task, HVT exploits the benefits of both approaches, thus resulting in superior behavioral performance as compared to variable priority alone (Gopher et al., 1994). Seventy-five participants were recruited for the current study and randomized to one of three groups: (1) FET, in which participants practiced the game, (2) HVT, in which participants practiced using a combination of part-task training and VPT, or (3) a Control group that received limited game play. All participants played the videogame inside an MRI scanner pre- and post-training, and neural recruitment during game performance was compared across groups as a function of training.

We hypothesized that both training groups would achieve a greater level of skill mastery than the control group, as demonstrated by a greater behavioral improvement in game performance, along with a reduction in the recruitment of the lateral prefrontal regions known to subserve cognitive control operations (Miller and Cohen, 2001). We reasoned that repeated practice on a task for 30 h would involve a transition from the effortful, resource-intensive earlier stages of skill acquisition to a stage of relative automaticity, characterized by a reduction in the need to exert top-down control, along with a concomitant decrease in the activity of the prefrontal cortices (Poldrack et al., 2005). In order to examine the effects of practice on the videogame on behavioral performance and neural recruitment, we merged data from the two training groups to evaluate first the effect of practice on the SF game, relative to a limited-contact control group. In our second set of analyses, we compared the two training groups directly to investigate the differential effect of strategy on behavior and cortical recruitment. A comparison of the two training strategies, we hypothesized, would show significantly greater skill mastery for the HVT group relative to the FET group, along with continued recruitment of the regions of the prefrontal cortices in the FET group, relative to the HVT group, demonstrating a greater need to exert top-down control in the face of sub-optimal strategies acquired due to simple practice on the complex task. In addition, we hypothesized that game play in FET participants would depend upon the motor network, involving the primary motor cortices and the supplementary motor areas, reflecting learning based on routine behavior and fixed skills (Myers et al., 2003).

MATERIALS AND METHODS

PARTICIPANTS

Seventy-five young adults were recruited for the current study from the Champaign-Urbana community via flyers and announcements posted throughout the University of Illinois campus. Interested participants were asked to fill out a survey collecting basic demographics, and measuring videogame play during the last 12 months (available at http://spacefortress.blogspot.com). Participants were excluded from the study if they indicated videogame play of more than 4 h per week, presence of any psychiatric or neurological condition, and left-handedness as assessed by the Edinburgh Handedness Inventory. Participants meeting eligibility criteria were initially randomly divided across three groups: (1) FET, (2) HVT, or (3) a no-contact control group. Halfway through the recruitment process, the basic demographics of the three groups were checked to ensure that no systematic differences existed across groups in age or gender. All participants were paid $15 an hour for their participation. The University of Illinois Institutional Review Board approved the study and all participants gave informed consent. Participant demographics for each of the three groups are displayed in **Table 1**. The groups did not differ on any of the demographic variables.

Of these 75 participants, 72 completed the MRI session pre- and post-training. Two participants were excluded because of problems in data acquisition. Four out of the remaining 70 participants were excluded from the current analyses because of excessive motion (greater than one functional voxel) in more than 10 functional T2* images in all three runs of the fMRI data. All analyses were conducted with the remaining 66 participants, whose demographics are also presented in **Table 1**. There were no statistically significant differences in age, gender, or education between the full sample and the subset that was analyzed for the current study. Please note that the behavioral data presented here have been previously reported in Lee et al. (2012), and that the current study focuses exclusively on the functional MRI data.

Table 1 | Descriptive characteristics of participants in the three training groups (FET, HVT, and control) based on all 75 participants and on the sample of 66 participants used for the analyses reported in this paper.

	Fixed Emphasis Training (FET)	Hybrid Variable-priority Training (HVT)	Control group
75 Participants			
N	25	25	25
Age	21.91 (2.78)	20.88 (2.07)	21.44 (2.52)
Proportion male	0.36	0.40	0.44
Self-rated health	5	5	5
Year of education	15.52 (2.20)	14.68 (1.85)	15.28 (2.25)
Baseline score	−844.45 (2086.82)	−1034.78 (1907.15)	−988.39 (1916.30)
66 Participants			
N	23	22	21
Age	22 (2.90)	20.86 (2.19)	21.48 (2.71)
Proportion male	0.34	0.41	0.47
Self-rated health	5	5	5
Year of education	15.61 (2.27)	14.68 (1.97)	15.24 (2.37)
Baseline score	−857.51 (1925.31)	−1102.02 (1909.59)	−860.40 (1926.95)

Standard deviations are within parentheses. No significant differences were found between the full sample and the subset of 66 participants on demographics or behavioral performance at Time 1 and Time 2. Total game score improvement was also not significantly different between the two groups. For self-related health, the scale was ranging from 1 for poor to 5 for excellent.

STUDY PROCEDURES

The present study employed a randomized controlled trial to examine the effects of training and training strategies on behavioral and neural functioning. All recruited participants were oriented to the game via a 20-min instructional video that detailed the requirements of the game (video also available at http://spacefortress.blogspot.com), followed by another 5-min summary video that reviewed the important rules. Following the video demonstration, all participants completed a pop-up quiz inquiring about instructions, and after ensuring that they had successfully understood the rules of the games and the operations involved, participants played six 3-min games. Following the game orientation session, all participants underwent a detailed cognitive assessment session (the results of which are reported in Lee et al., 2012), an event-related brain potential (ERP) session (which is not the focus of this manuscript), and a functional MRI session.

Participants successfully undergoing the assessment sessions were divided into three groups, two of which were training groups (FET and HVT) where participants completed fifteen 2-h sessions, resulting in 30 h of training on the videogame, SF. The third, control group received contact with the game at pre-training, after the training groups completed 10 h of training, and then again at post-training. Below we describe in brief the SF videogame, which was used as a platform in the current study to implement the different strategies and examine changes in cortical recruitment.

Space Fortress

The SF videogame was originally developed in a cognitive psychophysiology laboratory (Mané and Donchin, 1989) to provide a platform for the study of complex skill acquisition in an environment that was visually engaging, and modeled the complexities and multi-dimensionality of real-life tasks. As such, the SF game taps into perceptual, motor, executive and attentional skills, and thus lends itself as an ideal stage for the training of these various cognitive abilities, either through repeated practice on the whole game or training on different components to master the varied cognitive operations involved. This particular videogame has been used extensively in research studies (see Fabiani et al., 1989; Gopher et al., 1989; Mané and Donchin, 1989; Rabbitt et al., 1989; Boot et al., 2010; Maclin et al., 2011; Voss et al., 2011; Lee et al., 2012), and thus here we briefly discuss the game and outline the main components. A depiction of the SF game screen is presented in **Figure 1A**.

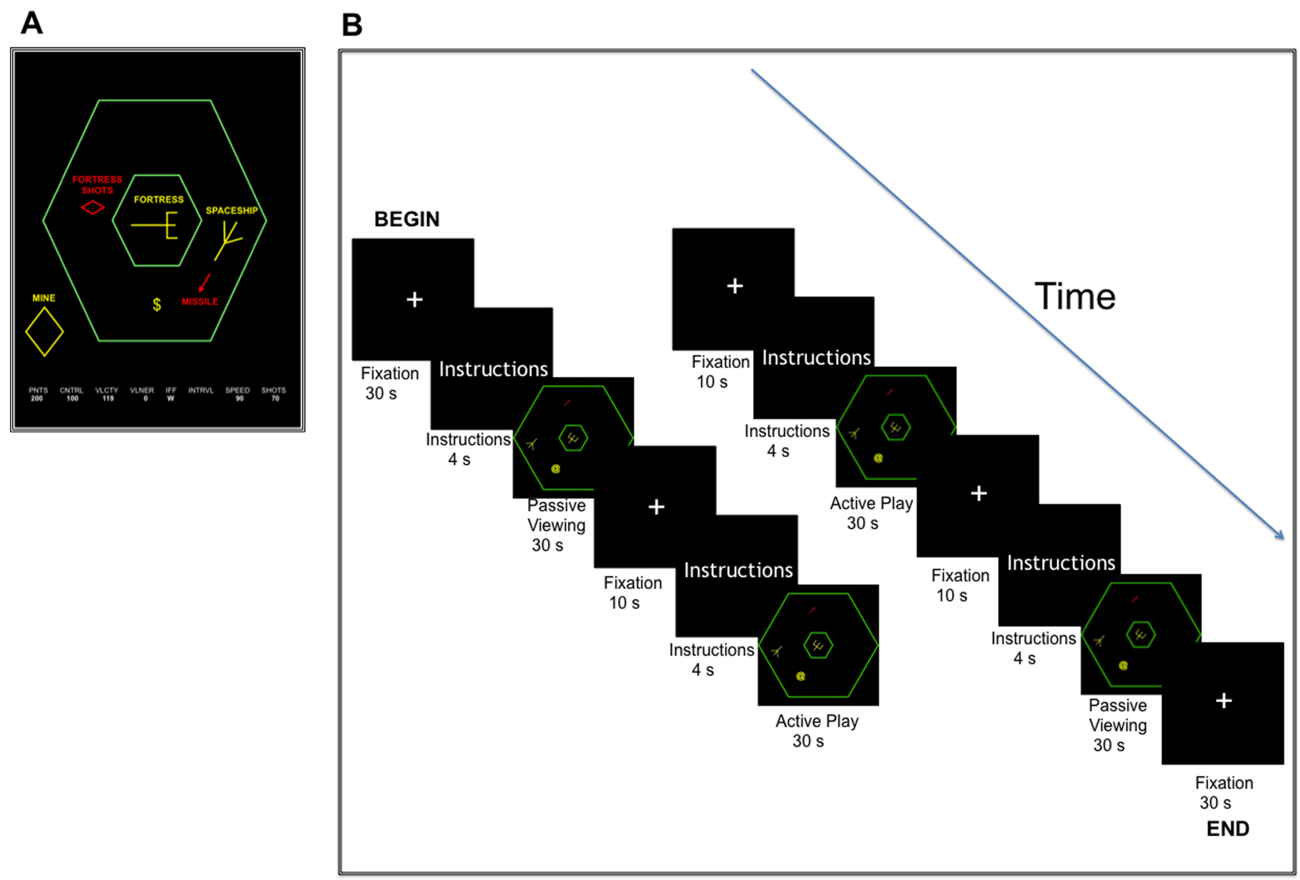

FIGURE 1 | Schematic representation of Space Fortress **(A)**, along with a graphical description of the SF MRI task design with blocks of active play and passive viewing interspersed with fixation periods **(B)**.

Players are awarded a total score for each game, which is the sum of four sub-scores (Control, Velocity, Speed, Points). The main task in the SF game is for the player, represented by a ship, to destroy a SF, which is located in the center of the screen within two hexagons, using missiles allotted to them. The ship flies in this environment with no brakes, so the player must exercise slight, precise movements of the joystick, keeping the ship in the large hexagon, and a failure to do so results in a reduction of Control scores. Successfully destroying the SF contributes to the Point sub-score. Players are penalized if they improperly execute the series of missile launches required to destroy the fortress and if the fortress' missiles hit the ship.

In addition, throughout the game, participants also have to deal with mines and acquire bonus points and missiles. Diamond-shaped foe or friend mines appear on the screen, with a corresponding letter that is displayed on the bottom of the screen indicating the friend or foe status of the mine. Correctly recognizing the mines and taking appropriate action contributes toward the Speed sub-score. However, if a mine is misidentified, the damage that the mine endures transfers to the ship and the player receives a deduction in the Speed sub-score.

Participants are also given opportunity to earn bonus missiles or bonus points, by constantly monitoring the appearance of a dollar sign in their field of play. To earn the bonus, participants are asked to stay vigilant of the appearance of a pair of dollar signs, and clicking the mouse buttons at the second, not the first dollar sign earns them bonus missiles or bonus points.

Training groups

The training groups employed in this study were modeled after the groups used in the Gopher et al.'s (1994) study to capitalize on the benefits of both part-task training and variable priority whole-task training to achieve accelerated skill acquisition. Our first training group, the FET group received no formal strategy training and were simply instructed to concentrate on obtaining as high a total score as possible, while focusing on the different components of SF equally. All participants in this group played thirty 3-min games of SF each session for 15 sessions.

The second training group, referred to as the HVT group combined both part-task training and VPT. A combination of part-task and VPT (combined sessions) was employed in the first five sessions, while exclusive VPT was used in the last 10 sessions. During the first hour and 10 min of the combined sessions, part-task training was employed, in which players practiced a specific component of SF that was presented separately from the rest of the game. For example, in a given game during part-task training, participants might be presented with the task of just navigating the ship or just aiming and firing. During the remaining 50 min of the combined session, participants in the HVT group were instructed to employ VPT. Participants played SF in its entirety with the goal of focusing on the specific skill that was previously learned in the part-task training and scoring as high a total score as possible on that particular component. The details of the part-task training are described in **Table 2**. In the last 10 sessions employing the VP strategy, participants were asked to emphasize different components of the game sequentially. In these sessions, participants completed five practice blocks of six trials emphasizing the four sub-scores.

Both training groups, at the start and end of every session, played three test games where total score was emphasized, and these data were used as behavioral data for pre- and post-game scores and used in all behavioral analyses and brain–behavior correlations.

BEHAVIORAL ANALYSES

To analyze the effects of videogame training on improvement on SF game performance, quantified by total score across all four components, we conducted two repeated-measures ANOVAs with time (pre-training, post-training) as the within-subjects factor and group as the between-subjects factor[1]. Gender was included as a covariate in the ANOVAs, as previous research had shown that gender differences exist in videogame performance (Terlecki and Newcombe, 2005; Feng et al., 2007). In the first ANOVA, to examine the influence of training on game performance, we merged the two training groups into one and tested whether training on the SF game was associated with improvements in total game score, relative to the control group. This ANOVA included time (pre-training, post-training) as a within-subjects factor and group (Control, Training) as a between-subjects factor.

In order to examine the influence of training strategy on game improvement, we conducted a second repeated-measures ANOVA with time (pre-training, post-training) as a within-subjects factor and training strategy as a between-subjects factor (HVT, FET). All behavioral data were analyzed using SPSS 17.0 for Mac.

Table 2 | Details of the part tasks implemented in the first five sessions.

Part-training details
1. Destroy Fortress by shooting
2. Slow down a ship
3. Aiming
4. Aiming and firing
5. Navigating a ship in trajectory 1
6. Navigating a ship in trajectory 2
7. Navigating a ship in trajectory 3
8. Navigating a ship in big hexagon
9. Navigating a ship in small hexagon
10. Navigating a ship in hexagon and aiming
11. Navigating a ship in hexagon, aiming, and firing
12. Navigating a ship in hexagon, aiming, and firing on the shooting fortress
13. Ship control only
14. Full game without bonus and mine
15. Mine control only
16. Bonus control only
17. Mine and bonus control
18. Mine and ship control
19. Bonus and ship control
20. Full game without bonus control
21. Full game without mine control

The first two part tasks were implemented only in the first two sessions, while the remaining part-tasks were implemented in all five part-task training sessions.

fMRI DATA ACQUISITION AND TASK PARAMETERS

Participants were scanned in a 3-Tesla Siemens Allegra head-only scanner at the Beckman Institute for Advanced Science and Technology at University of Illinois. Structural T1-weighted images were acquired using a 3-D magnetization prepared rapid gradient echo imaging (MPRAGE) protocol with 144 contiguous axial slices, collected in ascending order, echo time (TE) = 3.87 ms, repetition time (TR) = 1800 ms, field of view (FOV) = 256 mm, acquisition matrix 160 mm × 192 mm, slice thickness = 1.3 mm, and flip angle = 8°.

Functional T2* weighted images were acquired using a fast echo-planar imaging (EPI) sequence with blood oxygenation level-dependent (BOLD) contrast (64 × 64 matrix, 3.4 mm × 3.4 mm × 4.0 mm voxel size, TR = 2000 ms, TE = 25 ms, and flip angle = 80°, number of slices = 28). Using a MRI-compatible joystick, all participants completed three full runs of the SF game during MRI scanning at pre- and post-assessment. Presentation of SF during the MRI session was based on a block design consisting of two 30-s blocks of active game-play and two 30-s blocks of passive viewing, interspersed with 10-s fixation periods and 4-s of instructions. During blocks of active game-play, participants were instructed to play the game like they would play it in the laboratory, and during passive view, participants watched a video of an expert playing the videogame. A total of 115 volumes were collected for each functional run. A depiction of the SF MRI task design is presented in **Figure 1B**.

[1]Two separate ANOVAs were conducted to examine separately the effects of practice and training strategy on game score improvement. Given that the VP and FP groups both practiced the game for 30 h, we examined if practice on the game would result in overall improvement in game performance and thus for the first ANOVA data from the two groups were merged to examine this hypothesis. However, to examine if unequal differences in sample size between the practice groups (FP and VP combined) and the control group could result in significant effects on the ANOVA, we also conducted a repeated-measures ANOVA with all three groups in the model (Control, HVT, FET), with time as the within-Ss factor and gender as the covariate to examine the effects on a time × group interaction. With the three groups as the between Ss factor, we find a main effect of time [$F(1,62) = 21.19$, $p < 0.001$], group [$F(2,62) = 6.54$, $p < 0.005$], and a significant time × group effect [$F(2,62) = 23.03$, $p < 0.001$].

fMRI ANALYSES

Neuroimaging data were analyzed using FSL 4.1 and FEAT (fMRI Expert Analysis Tool). Images were corrected for motion using a rigid-body algorithm in MCFLIRT, and smoothed with a Gaussian high-pass filter of 100 s. Structural T1-weighted images were skull-stripped using a robust deformable brain extraction technique (BET). The skull-stripped images for each participant were transformed to a standard Montreal Neurological Institute (MNI) space and then spatially registered to each participant's high-resolution scan. All participants, as mentioned above, played three full runs of the SF game. Given that participants were required to play the videogame with a MRI-compatible joystick inside the fMRI scanner, we noticed significant motion for many participants across different runs of the game. For each participant, we decided to exclude one run with the lowest signal-to-noise ratio (SNR) and motion greater than 1 functional voxel space (3.475 mm) in 10 or more volumes. Final analyses were conducted with two runs of the SF game for each participant at pre- and post-training.

Following pre-processing, the functional data collected during the presentation of the SF game were convolved with a double-gamma function to model the response for each condition (active game playing and passive viewing). This first-level analysis, done separately for each participant for the two functional runs, resulted in voxel-wise parameter estimate maps for the entire brain for each condition (active, passive), and for the direct comparison between the conditions (Active > Passive). These parameter estimate maps and variance maps from the two functional runs were then aggregated within subject (across the two functional runs) for greater statistical power, using ordinary least squares (OLS) in FSL's FEAT tool. This was done separately for Time 1 and Time 2 to examine recruitment of cortical regions during active game play before and after the intervention for each individual participant.

Finally, the mean individual-level statistical maps from the two time-points were forwarded to a third-level fixed effects, individual-level longitudinal analysis to examine the influence of training on neural recruitment during active game playing and passive viewing separately for each individual participant. This was done using OLS in FSL's FEAT tool. This third-level analysis resulted in statistical maps representing activation during active game playing and passive viewing at pre-training, post-training and the contrast between the two time-point for each individual participant. These parameter estimates were forwarded to two separate fourth-level, mixed-effects analyses, paralleling the behavioral analyses that considered between-subject variation. Both these analyses were conducted using FLAME (fMRIB's Local Analysis of Mixed Effects). All statistical maps were thresholded at a voxel-wise z-score of 2.33 ($p < 0.01$) and a cluster-wise threshold of $p < 0.05$, with a minimum cluster size of five hundred and twenty-two 2 mm^3 voxels.

The first higher-level analysis was conducted to locate regions of cortex that showed an influence of training on cortical recruitment during active game play. For this, we examined the contrast of Active > Passive game play for the three groups. Here, we were primarily interested in changes in neural recruitment following post-training in the control group relative to the training groups. We examined changes at post-training relative to pre-training (T2 > T1) in the contrasts of Control > Training and Training > Control. Regions of interest (ROIs) from this whole-brain analysis comparing the control group to the training groups were identified to examine associations with behavioral improvement in the SF game. Specifically, statistical peaks in separable anatomical regions as demarcated by the Harvard-Oxford cortical atlas, packaged with the FSL software package (FSL 4.1.4, FMRIB's Software Library, www.fmrib.ox.ac.uk/fsl) in the contrast of Control > Training from T2 > T1 were taken to examine brain–behavior relationships. We then created a 14-mm sphere around each of these statistical peaks and extracted percent signal change for the contrast of Active > Passive for both pre- and post-training, to examine associations with game improvement.

In addition, we were also interested in examining how cortical recruitment in these regions differed as a function of training strategy. We extracted percent signal change from these regions at pre- and post-training and conducted an independent samples t-test comparing differences in change in cortical recruitment from pre- to post-training between the two training groups.

The second higher-level analysis was conducted to directly compare cortical recruitment for the two training strategies to better understand the neural correlates involved with accelerated skill acquisition in the HVT group relative to the FET group. The above ROI analysis represented a focused examination of the changes in cortical activation in the two training groups in functional regions that showed continued activation in the control group, relative to the training groups. In this whole-brain analysis, independent of the control group, we examined differential cortical recruitment in the two training groups at post-training, relative to pre-training. Statistical peaks in this contrast were also taken to create ROIs for examining brain–behavior associations.

RESULTS

BEHAVIORAL RESULTS

The effect of training on behavioral performance was examined using a repeated-measures ANOVA with time (pre-training, post-training) as a within-subjects factor and group (control, training) as a between-subjects factor. We found a main effect of time [$F(1,63) = 15.4$, $p < 0.01$], indicating that all groups had significant improvement in total game score from Time 1 to Time 2, along with a significant Time × Group interaction [$F(1,63) = 40.0$, $p < 0.01$], suggesting that training across both strategies was beneficial for behavioral performance in the SF game, relative to the control group (**Figure 2**).

To examine whether HVT as a training strategy was related to greater levels of game mastery in comparison to FET, we contrasted HVT and FET using a repeated-measures ANOVA, using the average total score from SF at Time 1 and Time 2 as a within-subjects factor and group as a between-subjects factor. We found a main effect of time [$F(1,42) = 18.8$, $p < 0.01$] as well as a significant Group × Time interaction [$F(1,42) = 4.72$, $p < 0.05$], which indicated a greater benefit on SF game performance for the HVT group relative to the FET group. This suggests that a training strategy combining part-training with variable priority is more beneficial than practice alone on the SF game (**Figure 2**).

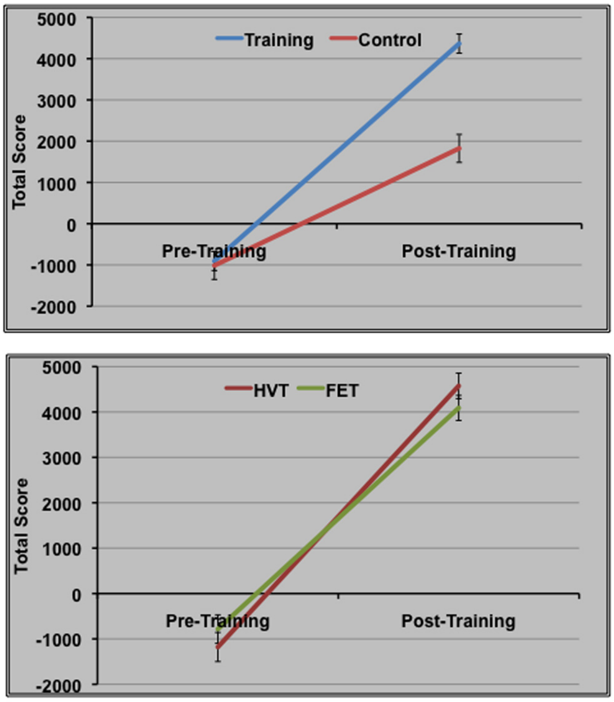

FIGURE 2 | Space Fortress behavioral data for the three groups at pre- and post-training.

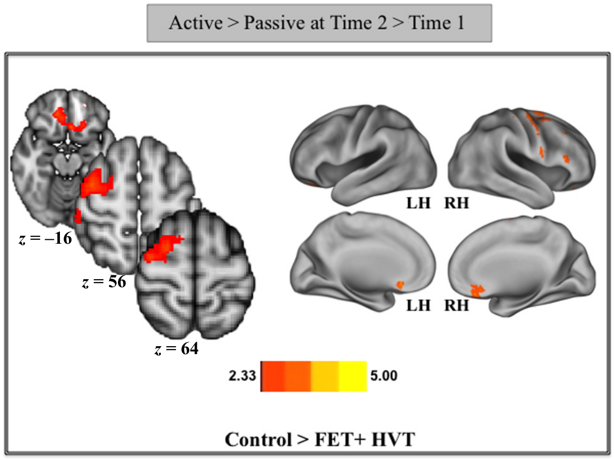

FIGURE 3 | Cortical areas recruited by the controls relative to the two training groups at post-training, when compared to pre-training. All axial slices are presented in radiological orientation.

Table 3 | Statistical peaks of cortical regions recruited during the Active > Passive condition at Time 2 > Time 1 contrasting the control group with the training groups (Control > Training).

Anatomical region	Label	Max *z*-stat	MNI coordinates		
			X	*Y*	*Z*
Right middle frontal gyrus	Rt. MFG	3.39	44	0	56
Right superior frontal gyrus	Rt. SFG	3.57	34	62	70
Ventral medial prefrontal cortex	vmPFC	2.68	22	−2	68

NEUROIMAGING RESULTS

Practice-related differences in cortical recruitment and associations with behavioral performance

In order to examine the effects of practice on neural recruitment during active game play, we conducted a whole-brain analysis contrasting brain activation during the Active > Passive condition at Time 2 > Time 1, separately comparing the control group to the training groups. A contrast of the control group and the training groups (Control > Training) showed decreased activation of the right middle frontal gyrus (rt. MFG), right superior frontal gyrus (rt. SFG), and ventral medial prefrontal cortex (vmPFC), for the training groups relative to the control group (**Figure 3**). **Table 3** provides the max *z*-stat values in MNI space for the peak voxels in this contrast. In line with our hypothesis, these results demonstrate that videogame training, in comparison to the control condition, results in a reduced need for activation of attentional areas during game-play (**Figure 3**). Statistical peaks in this contrast were taken to create ROIs, which were then examined for associations with behavioral performance. For this, we conducted partial correlations, controlling for the effects of gender between game improvement from pre- to post-training and percent signal change in regions identified in the contrast of Control > Training. We found a negative relationship between game improvement and increase in activation in the right MFG ($r = -0.31$, $p < 0.01$) and a trend for a negative association for the right SFG ($r = -0.22$, $p = 0.08$), such that individuals showing a greater increase in activation of these regions from pre- to post-training also demonstrated the lowest gains in game improvement.

Training strategy-related differences in cortical recruitment and associations with behavioral performance

The above identified functional ROIs from the contrast of Control > Training were also examined for differences as a function of training strategy. As seen in **Figure 4**, the FET group showed greater increase in activation than the HVT group at Time 2 relative to Time 1 for all ROIs; however, significant increases in activation were noted for the right MFG and right SFG ($p < 0.05$) in comparison to HVT after training. This finding suggests that individuals in the FET group required continued activation of the prefrontal cortices in order to meet the demands of the SF game, whereas individuals in the HVT group showed reduced recruitment of these prefrontal regions as a function of the training strategy.

While the above discussed ROI analysis represented a focused examination of the effects of training strategy on the recruitment of cortical areas that showed a reduction in the contrast of Control > Training, we also conducted a whole-brain analysis comparing the two strategies to examine cortical and sub-cortical structures that were differentially recruited by the two groups at post-assessment. We found greater recruitment of the bilateral primary motor cortices, somatosensory cortices, supplementary motor area, and the posteromedial cortex, including the

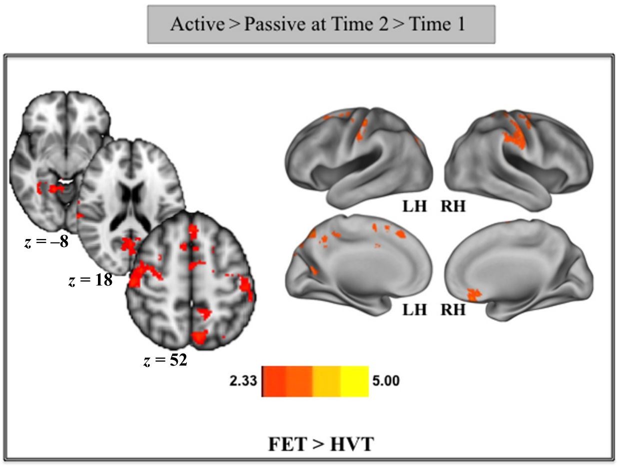

FIGURE 4 | Change in percent signal change from pre- to post-training in the cortical areas found in the contrast of Control > Training for all three groups.

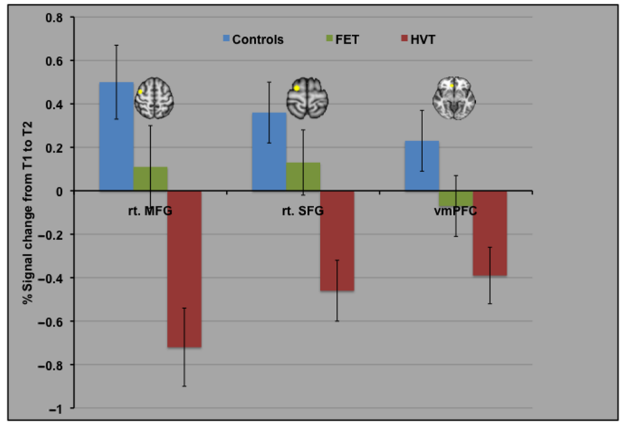

FIGURE 5 | Cortical areas recruited by the FET participants relative to the HVT participants at post-training, when compared to pre-training. All axial slices are presented in radiological orientation.

precuneus, and the retrosplenial cortex (see **Figure 5** and **Table 4**) in FET participants post-training, relative to the HVT participants. The contrast of HVT > FET did not result in any significant clusters of activation.

Statistical peaks in these regions were taken to examine associations with behavioral performance across participants, while controlling for the effects of gender. We found a trend for negative associations between game score improvement and increase in activation in the right and the left motor cortices across all participants ($r = -0.22$, $p = 0.08$, and $r = -0.23$, $p = 0.06$ respectively), again suggesting that greater recruitment of the motor cortices with training was associated with poor behavioral improvements on the SF game.

Table 4 | Statistical peaks of cortical regions recruited during the Active > Passive condition at Time 2 > Time 1 contrasting the FET group with the HVT group (FET > HVT).

Anatomical region	Label	Max *z*-stat	MNI coordinates		
			X	*Y*	*Z*
Right primary motor cortex	rt. M1	2.72	42	−8	56
Left primary motor cortex	lt. M1	2.7	−44	−12	56
Right postcentral gyrus	Rt. postcentral gyrus	3.56	60	−14	40
Left postcentral gyrus	Lt. postcentral gyrus	3.14	−58	−18	40
Supplementary motor area	SMA	2.86	−2	−4	54
Posteromedial cortex	PMC	2.73	2	−56	38

DISCUSSION

The present study, employing the SF videogame as a context to study multi-tasking and skill acquisition in a complex task, investigated the effects of two types of training strategies in enhancing performance and neural recruitment during videogame play. In line with our hypotheses, we found that videogame training enhanced behavioral performance on a complex task and concurrently reduced the neural demands of SF in areas associated with greater attentional control. In addition, comparing the two training strategies, we found greater training-related improvements associated with HVT relative to FET, along with a reduced need to recruit cortical circuitry subserving executive control and motor performance. Based on these results, HVT is proposed as an effective strategy for accelerating skill acquisition and achieving mastery.

Extensive research supports the utility of repeated practice to enhance behavioral performance (Fabiani et al., 1989; Gopher et al., 1994; Boot et al., 2010). Corroborating these findings, our study reports that repeated exposure to SF leads to higher levels of game mastery in novice videogame players. Across all three groups, participants showed improvement in behavioral performance from pre- to post-training, indicating a beneficial effect of basic practice on a complex task (Newell and Rosenbloom, 1981). In addition, we found evidence for superior behavioral performance with a strategy that involved a combination of part-task training, and variable whole-task training, thus adding to the existing literature favoring flexible strategies in acquisition of complex skills relative to constant, repeated practice on the task (Boot et al., 2010; Voss et al., 2011).

To investigate the neural mechanisms associated with videogame training, we also examined the influence of training on functional brain activity. Given that training on the SF game was expected to reduce the attentional demands associated with game-play, we predicted an attenuation of neural activity in areas of the prefrontal and parietal cortices as a result of training. Confirming this hypothesis, we found reduced activation in cortical regions involved in attentional control for the training groups relative to the control group, and also for HVT relative to FET. Specifically, the control group exhibited continued activation in regions of the frontal cortices, including the middle frontal gyrus, and the superior frontal gyrus. These lateral prefrontal regions are traditionally known to be involved in processes of top-down control (Miller and Cohen, 2001; Erickson et al., 2009), showing enhanced activation with increasing task demands (Braver et al., 1997; Prakash et al., 2009) and a reduction in activity with relative automaticity of the task (Poldrack et al., 2005). This suggests that the poorer performance of the control group relative to the training groups may, therefore, be related to ineffective control of the joystick during game-play, greater effort in multi-tasking between the different components of the game, and a general enduring need for cortical recruitment in support of task-focused performance. In comparison, the reduced activation of such regions observed in the training groups relative to the control group at post-training represents training-related optimization of neural recruitment during game-play.

An important concept in the acquisition of a complex skill, proposed by Gopher et al. (1989) is the development of higher-order schemas as learners progress through the various stages of skill acquisition and attain mastery of the task. Schemas can be conceptualized as organized series of responses, usually formed after repeated and optimal practice with a task, resulting in efficient performance on the task with minimal resources. The vmPFC is known to be selectively involved in the effortful retrieval of consolidated memory traces that are consistent with pre-existing schemas (van Kesteren et al., 2010), such that greater activation is seen in this region for recall of remote memories, similar to that seen in the hippocampus for recall of recent memories (Frankland and Bontempi, 2005; Takashima et al., 2006). One explanation for the greater activation of the medial prefrontal regions during remote memory recall is the greater effort required to retrieve a degraded and weak schema (Frankland and Bontempi, 2006; Rudy et al., 2006). In our study, we found control participants to show greater activation in the vmPFC than training participants at post-intervention, thus, possibly suggesting a failure to form a well-organized series of responses for the SF game in the control group, resulting in greater neural effort. Training strategies that involve repeated exposure to the game possibly result in the building of higher-order schemas that represent well-organized sequences of responses (Gopher et al., 1989; Kantak et al., 2010). For the control group, due to limited exposure to the SF game, well-organized schemas representing connections between the different elements of the game may not have been built, and thus, we see greater effort being exerted to retrieve a weak memory trace. In contrast, the two training groups did not differ in activation of the medial prefrontal cortices, suggesting that exposure to the game for 30 h results in the development of higher-order schemas, which can be efficiently retrieved at the time of need.

Thus, whereas game performance on SF led to a persistent taxing of the attentional network, specifically the prefrontal cortices in control participants, individuals in the training groups demonstrated successful performance on a complex task using minimal allocation of attentional resources. In addition, we found continued activation of attentional areas for FET at post-training, which might reflect the inefficient use of two different cognitive control networks in this group (Voss et al., 2011) and their enduring reliance on attentional resources to meet the demands of SF. Our study shows that the attentional costs of multi-tasking, exemplified in lower scores on SF and continual activation of the prefrontal cortices after training (Dove et al., 2000; Gazzaley et al., 2005), are more pronounced for FET than HVT, a finding which predicates the employment of the HVT cognitive training strategy (uniquely involving variable emphasis on different task components combined with basic part-task practice) as a useful approach to improving cognitive functioning. Based on a modest association between game score improvement and decreased activation of the right MFG, we also suggest that such reductions in cortical recruitment, observed in the HVT group, could indeed be related to improved performance on SF. Since decreased recruitment of the cortical regions comprising the attentional network can have implications for behavioral performance, an effective cognitive training tool is one that concurrently hones behavioral skills and optimizes the neural circuitry of attentional control.

Differences in cortical recruitment between the two groups were also seen in the primary motor cortices, the sensory cortices, and the supplementary motor area, with the FET group showing continuing reliance on these areas post-training relative to the HVT group. The involvement of the motor network during the SF game is not surprising given that the control of the ship in the frictionless environment is arguably the most challenging component of this complex task. In fact, greater phasic activity in the right motor cortex during baseline SF play has been found to be beneficial to game performance (Anderson et al., 2011), suggesting that activity in this region is important for learning the game. In fact, both positron-emission tomography (PET) studies (Jenkins et al., 1994; Schlaug et al., 1994) and lesion studies (Pavlides et al., 1993) provide evidence for the involvement of the motor network including the primary motor cortices, the sensorimotor cortices, and the somatosensory cortices in initial acquisition of motor skills, with significant attenuation of activity within the motor network with consolidation of the motor skill as a unitary motor plan (Pascual-Leone et al., 1994). Thus, the continued engagement of the motor network in participants trained under constant practice (FET) suggests the reliance of this strategy on the procedural system, guided by fixed rules and learning. Given that interference with these regions attenuates retention of motor skills following FET (Kantak et al., 2010), suggests the critical involvement of these regions with this practice structure that focuses exclusively on repeated practice of the task, rather than flexible development of strategies and skills that will aid in efficient performance. Indeed, greater recruitment of the primary motor cortices from pre- to post-training was associated with lower gains on the SF task, thus suggesting that individuals demonstrating the greatest improvements in performance as a function of training, also showed a significant decline in their reliance on the motor network.

The addition of neuroimaging techniques provides insight into the influence of videogame training on changes in neural activity during a complex task. Another particular strength of this study is the inclusion of a no-contact control group and a non-VPT group, which previous SF studies have not considered. This is particularly useful because it serves to clarify the confounds present in previous studies between the behavioral and neural characteristics of VPT-based training (HVT) and simple practice effects (FET). For future research it would be important to directly compare the effects of the HVT group to that of the variable training, fixed emphasis, and a no-contact control group to truly parse out the effects of the hybrid approach relative to the variable training approach and the fixed emphasis approach. An important limitation of the current study was the collection of neural data after 30 h of training, as opposed to assessing changes in neural functioning after a shorter period of training. Since differences in behavioral performance between HVT and FET were predominant after 10 h of training (reported in Lee et al., 2012), we suspect that 30 h of videogame training may have not entirely captured neural differences between the two training groups when performance differences were at their maximum. Although a comparison of the training groups in this study indicates a significant advantage for participants in the HVT group, this advantage could potentially be more evident if measured earlier in training. Therefore, future studies examining changes in neural recruitment earlier in training would be critical to understanding the dose–response relationship between training and neural recruitment.

Previous studies of attentional and executive control have established that cortical recruitment of the regions comprising the attentional network is responsive to task demands (Banich et al., 2000; Dove et al., 2000). However, the role of this additional neural activation has been disputed, with some studies suggesting that activation may serve a compensatory function (Davis et al., 2008), while others argue that excessive attentional network activation is related to diminished performance on a cognitive task (Gazzaley et al., 2005; Prakash et al., 2009). The aging literature, for example, has associated extensive cortical recruitment in older adults with poorer performance on a cognitive task (Prakash et al., 2009; see also Schneider-Garces et al., 2010). Thus, the implementation of a randomized controlled trial similar to the one used in the present study could shed light on the neural correlates associated with improved executive function in older adults and represents a potentially interesting and valuable study for future investigations.

In summary, the present study provides evidence for the ability of videogame training to enhance performance on a complex task and correspondingly decrease cortical recruitment of attentional resources. Based on behavioral and neuroimaging evidence, we conclude that HVT, relative to FET, may facilitate greater mastery of a complex task and neural efficiency in response to task difficulty. In general, videogame training signifies a novel and promising avenue to improving cognition and maximizing efficiency in neural recruitment, thereby making it a plausible tool for use with clinical populations in the future.

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AUTHOR CONTRIBUTIONS

Hyunkyu Lee, Michelle W. Voss, Walter R. Boot, Chandramallika Basak, Monica Fabiani, Gabriele Gratton, Arthur F. Kramer, and Ruchika S. Prakash designed the behavioral and fMRI components of the study. Hyunkyu Lee, Michelle W. Voss, Walter R. Boot, and Ruchika S. Prakash collected the imaging data. Ruchika S. Prakash, Angeline A. De Leon, Lyla Mourany, Hyunkyu Lee, and Michelle W. Voss analyzed the behavioral and imaging data. Ruchika S. Prakash and Angeline A. De Leon wrote the paper and all co-authors edited the manuscript.

REFERENCES

Ackerman, P. L. (1988). Determinants of individual differences during skill acquisition: cognitive abilities and information processing. *J. Exp. Psychol. Gen.* 117, 288–318.

Anderson, J. R., Bothell, D., Fincham, J. M., Anderson, A. R., Poole, B., and Qin, Y. (2011). Brain regions engaged by part- and whole-task performance in a video game: a model-based test of the decomposition hypothesis. *J. Cogn. Neurosci.* 23, 3983–3997.

Banich, M. T., Milham, M. P., Atchley, R. A., Cohen, N. J., Webb, A., Wszalek, T., Kramer, A. F., Liang, Z., Barad, V., Gullett, D., Shah, C., and Brown, C. (2000). Prefrontal regions play a predominant role in imposing an attentional 'set': evidence from fMRI. *Brain Res. Cogn. Brain Res.* 10, 1–9.

Basak, C., Boot, W. R., Voss, M., and Kramer, A. F. (2008). Can training in a real-time strategy videogame attenuate cognitive decline in older adults? *Psychol. Aging* 23, 765–777.

Bherer, L., Kramer, A. F., Peterson, M. S., Colcombe, S., Erickson, K., and Becic, E. (2008). Transfer effects in task set cost and dual task cost after dual-task training in older and younger adults: further evidence for cognitive plasticity in attentional control in late adulthood. *Exp. Aging Res.* 34, 188–219.

Boot, W. R., Basak, C., Erickson, K. I., Neider, M., Simons, D. J., Fabiani, M., Gratton, G., Voss, M. W., Prakash, R., Lee, H., Low, K. A., and Kramer, A. F. (2010). Transfer of skill engendered by complex task training under conditions of variable priority. *Acta Psychol.* 135, 349–357.

Boot, W. R., Blakely, D. P., and Simons, D. J. (2011). Do action video games improve perception and cognition? *Front. Psychol.* 2:226. doi: 10.3389/fpsyg.2011.00226.

Braver, T. S., Cohen, J. D., Nystrom, L. E., Jondies, J., Smith, E. E., and Noll, D. C. (1997). A parametric study of prefrontal cortex involvement in human working memory. *Neuroimage* 5, 49–62.

Chiaravalloti, N. D., DeLuca, J., Moore, N. B., and Ricker, J. H. (2005). Treating learning impairments improves memory performance in multiple sclerosis: a randomized clinical trial. *Mult. Scler.* 11, 58–68.

Craik, F. I., Govoni, R., Naveh-Benjamin, M., and Anderson, N. D. (1996). The effects of divided attention on encoding and retrieval processes in human memory. *J. Exp. Psychol. Gen.* 125, 159–180.

Davis, S. W., Dennis, N. A., Daselaar, S. M., Fleck, M. S., and Cabeza, R. (2008). Que PASA? The posterior–anterior shift in aging. *Cereb. Cortex* 18, 1201–1209.

Donchin, E., Fabiani, M., and Sanders, A. (1989). *The Learning Strategies Program: An Examination of the Strategies in Skill Acquisition.* Amsterdam: Elsevier.

Dove, A., Pollmann, S., Schubert, T., Wiggins, C. J., and von Cramon, D. Y. (2000). Prefrontal cortex activation in task switching: an event-related fMRI study. *Brain Res. Cogn. Brain Res.* 9, 103–109.

Erickson, K. I., Colcombe, S. J., Wadhwa, R., Bherer, L., Peterson, M. S., Scalf, P. E., Kim, J. S., Alvardo, M., and Kramer, A. F. (2007). Training-induced functional activation changes in dual-task processing: an fMRI study *Cereb. Cortex* 17, 192–204.

Erickson, K. I., Prakash, R. S., Kim, J. S., Sutton, B. P., Colcombe, S. J., and Kramer, A. F. (2009). Top-down attentional control in spatially coincident stimuli enhances activity in both task-relevant and task-irrelevant regions of cortex. *Behav. Brain Res.* 197, 186–197.

Fabiani, M., Buckley, J., Gratton, G., Coles, M. G. H., Donchin, E., and Logie, R. (1989).The training of complex task performance. *Acta Psychol.* 71, 259–299.

Feng, J., Spence, I., and Pratt, J. (2007). Playing an action video game reduces gender differences in spatial cognition. *Psychol. Sci.* 18, 850–855.

Fitts, P., and Posner, M. I. (1967). *Human Performance.* Belmont, CA: Brooks/Cole.

Frankland, P. W., and Bontempi, B. (2005). The organization of recent and remote memories. *Nat. Rev. Neurosci.* 6, 119–130.

Frankland, P. W., and Bontempi, B. (2006). Fast track to the medial prefrontal cortex. *Proc. Natl. Acad. Sci. U.S.A.* 103, 509–510.

Frederiksen, J. R., and White, B. Y. (1989). An approach to training based upon principled task decomposition. *Acta Psychol.* 71, 89–146.

Gazzaley, A., Cooney, J. W., McEvoy, K., Knight, R. T., and D'Espsito, M. (2005). Top-down enhancement and suppression of the magnitude and speed of neural activity. *J. Cogn. Neurosci.* 17, 507–517.

Gopher, D., Weil, M., and Bareket, T. (1994). Transfer of skill from a computer game trainer to flight. *Hum. Factors* 36, 387–405.

Gopher, D., Weil, M., and Siegel, D. (1989). Practice under changing priorities: an approach to the training of complex skills. *Acta Psychol.* 71, 147–177.

Jenkins, I. H., Brooks, D. J., Nixon, P. D., Frackowiak, R. S. J., and Passingham, R. E. (1994). Motor sequence learning: a study with positron emission tomography. *J. Neurosci.* 14, 3775–3790.

Kantak, S. S., Sullivan, K. J., Fisher, B. E., Knowlton, B. J., and Winstein, C. J. (2010). Neural substrates of motor memory consolidation depend on practice structure. *Nat. Neurosci.* 13, 923–925.

Kramer, A. F., Larish, J. F., and Strayer, D. L. (1995). Training for attentional control in dual task settings: a comparison of young and old adults. *J. Exp. Psychol. Appl.* 1, 50–76.

Kramer, A. F., Larish, J. F., Weber, T., and Bardell, L. (1999). "Training for executive control: task coordination strategies and aging," in *Attention and Performance XVII*, eds D. Gopher and A. Koriat (Cambridge, MA: MIT Press), 617–652.

Lee, H., Boot, W. R., Basak, C., Voss, M. W., Prakash, R. S., Erickson, K. I., Neider, M., Simons, D. J., Fabiani, M., Gratton, G., Low, K. A., and Kramer, A. F. (2012). Effective training of complex tasks: how strategy and individual differences contribute to performance, improvement, and transfer of training. *Acta Psychol.* 139, 146–158.

Maclin, E. L., Mathewson, K. E., Low, K. A., Boot, W. R., Kramer, A. F., Fabiani, M., and Gratton, G. (2011). Learning to multitask: effects of video game practice on electrophysiological indices of attention and resource allocation. *Psychophysiology* 48, 1173–1183.

Mané, A., and Donchin, E. (1989). The Space Fortress game. *Acta Psychol.* 71, 17–22.

Miller, E. K., and Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annu. Rev. Neurosci.* 24, 167–202.

Myers, C. E., Shohamy, D., Gluck, M. A., Grossman, S., Kluger, A., Ferris, S., Golomb, J., Schnirman, G., and Schwartz, R. (2003). Dissociating hippocampal versus basal ganglia contributions to learning and transfer. *J. Cogn. Neurosci.* 15, 185–193.

Newell, A., and Rosenbloom, P. S. (1981). "Mechanisms of skill acquisition and the law of practice," in *Cognitive Skills and Their Acquisition*, ed. J. R. Anderson (Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.), 1–55.

Olesen, P., Westerberg, H., and Klingberg, T. (2004). Increased prefrontal and parietal activity after training of working memory. *Nat. Neurosci.* 7, 75–79.

Pascual-Leone, A., Grafman, J., and Hallett, M. (1994). Modulation of cortical motor output maps during development of implicit and explicit knowledge. *Science* 263, 1287–1289.

Pavlides, C., Miyashita, E., and Asanuma, H. (1993). Projection from the sensory to the motor cortex is important in learning motor skills in monkeys. *J. Neurophysiol.* 70, 733–741.

Piaget, J. (1954). *The Construction of Reality in the Child.* New York: Basic Books.

Poldrack, R. A., Sabb, F. W., Foerde, K., Tom, S. M., Asarnow, R. F., Bookheimer, S. Y., and Knowlton, B. J. (2005). The neural correlates of motor skill automaticity. *J. Neurosci.* 25, 5356–5364.

Prakash, R. S., Erickson, K. I., Colcombe, S. J., Kim, J. S., Voss, M. W., and Kramer, A. F. (2009). Age-related differences in the involvement of the prefrontal cortex in attentional control. *Brain Cogn.* 71, 328–335.

Rabbitt, P., Banerji, N., and Szemanski, A. (1989). Space Fortress as an IQ test? Predictions of learning and practiced performance in a complex interactive video-game. *Acta Psychol.* 71, 243–257.

Rudy, J. W., Biedenkapp, J. C., and O'Reilly, R. (2006). Prefrontal cortex and the organization of recent and remote memories: an alternative view. *Learn. Mem.* 12, 445–446.

Schlaug, G., Knorr, U., and Seitz, R. J. (1994). Inter-subject variability of cerebral activations in acquiring a motor skill: a study with positron emission tomography. *Exp. Brain Res.* 98, 523–534.

Schneider, W., and Shiffrin, R. M. (1977). Controlled and automatic human information processing: II. Perceptual learning, automatic attending, and a general theory. *Psychol. Rev.* 84, 127–190.

Schneider-Garces, N. J., Gordon, B. A., Brumback-Peltz, C. R., Shin, E., Lee, Y., Sutton, B. P., Maclin, E. L., Gratton, G., and Fabiani, M. (2010). Span, CRUNCH and beyond: working memory capacity and the aging brain. *J. Cogn. Neurosci.* 22, 655–669.

Slagter, H. A., Davidson, R. J., and Lutz, A. (2011). Mental training as a tool in the neuroscientific study of brain and cognitive plasticity. *Front. Hum. Neurosci.* 5:17. doi: 10.3389/fnhum.2011.00017

Smith, M. E., McEvoy, L. K., and Gevins, A. (1999). Neurophysiological indices of strategy development and skill acquisition. *Cogn. Brain Res.* 7, 389–404.

Stern, Y., Blumen, H. M., Rich, L. W., Richards, A., Herzberg, G., and Gopher, D. (2011). Space Fortress game training and executive control in older adults: a pilot intervention. *Neuropsychol. Dev. Cogn. B Aging Neuropsychol. Cogn.* 18, 653–677.

Takashima, A., Petersson, K. M., Rutters, F., Tendolkar, I., Jensen, O., Zwarts, M. J., McNaughton, B. L., and Fernandez, G. (2006). Declarative memory consolidation in humans: a prospective functional magnetic resonance imaging study. *Proc. Natl. Acad. Sci. U.S.A.* 103, 756–761.

Terlecki, M. S., and Newcombe, N. S. (2005). How important is the digital divide? The relation of computer and videogame usage to gender differences in mental rotation ability. *Sex Roles* 53, 433–441.

van Kesteren, M. T. R., Rijpkema, M., Ruiter, D. J., and Fernandez, G. (2010). Retrieval of associative information congruent with prior knowledge is related to increased medial prefrontal activity and connectivity. *J. Neurosci.* 30, 15888–15894.

Voss, M. W., Prakash, R. S., Erickson, K. I., Boot, W. R., Basak, C., Neider, M. B., Simons, D. J., Fabiani, M., Gratton, G., and Kramer, A. F. (2011). Effects of training strategies implemented in a complex videogame on functional connectivity of attentional networks. *Neuroimage* 59, 138–148.

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On the impacts of working memory training on executive functioning

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Recent studies have reported improvements in a variety of cognitive functions following sole working memory (WM) training. In spite of the emergence of several successful training paradigms, the scope of transfer effects has remained mixed. This is most likely due to the heterogeneity of cognitive functions that have been measured and tasks that have been applied. In the present study, we approached this issue systematically by investigating transfer effects from WM training to different aspects of executive functioning. Our training task was a demanding WM task that requires simultaneous performance of a visual and an auditory *n*-back task, while the transfer tasks tapped WM updating, coordination of the performance of multiple simultaneous tasks (i.e., dual-tasks) and sequential tasks (i.e., task switching), and the temporal distribution of attentional processing. Additionally, we examined whether WM training improves reasoning abilities; a hypothesis that has so far gained mixed support. Following training, participants showed improvements in the trained task as well as in the transfer WM updating task. As for the other executive functions, trained participants improved in a task switching situation and in attentional processing. There was no transfer to the dual-task situation or to reasoning skills. These results, therefore, confirm previous findings that WM can be trained, and additionally, they show that the training effects can generalize to various other tasks tapping on executive functions.

Keywords: working memory training, transfer, executive functions

INTRODUCTION

In recent years, interest toward "brain training" and its mechanisms has risen with a growing pace. Such training involves improving cognitive functions, which have previously been considered as stable abilities that cannot be affected by training. One of the most studied topics in this area has been working memory (WM) training. The concept of WM refers to a limited-capacity system that includes a short-term storage of information and the functions of updating and manipulating the storage contents. Studies have shown that the capacity of WM predicts performance in several other cognitive tasks ranging from simple attentional tasks (Kane et al., 2001; Bleckley et al., 2003; Fukuda and Vogel, 2009) to tasks tapping more complex abilities, such as reading comprehension (Daneman and Carpenter, 1980), reasoning and problem-solving (Kyllonen and Christal, 1990; Engle et al., 1991; Fry and Hale, 1996; Barrouillet and Lecas, 1999; Engle et al., 1999), along with executive functioning in everyday life (Kane et al., 2007). Accordingly, one could expect that training-related increases in WM efficiency are reflected as improvements in several other functions.

And indeed, in addition to reports on successful training of WM (Klingberg et al., 2002, 2005; Westerberg et al., 2007; Holmes et al., 2009, 2010; Thorell et al., 2009), there is nowadays evidence that WM training can optimize an individual's performance in a comprehensive range of other cognitive measures, such as cognitive control (Klingberg et al., 2002, 2005; Westerberg and Klingberg, 2007; Chein and Morrison, 2010), fluid intelligence (Gf) (Klingberg et al., 2002; Olesen et al., 2004; Jaeggi et al., 2008), episodic memory (Dahlin et al., 2008a; Schmiedek et al., 2010; Richmond et al., 2011), and reading comprehension (Chein and Morrison, 2010). Moreover, WM training seems to be effective for different participant groups, including young adults (Klingberg et al., 2002; Dahlin et al., 2008a; Jaeggi et al., 2008, 2010; Chein and Morrison, 2010), older adults (Schmiedek et al., 2010; Richmond et al., 2011), stroke patients (Westerberg et al., 2007), children with WM deficits (Holmes et al., 2009), and children with attention deficit/hyperactivity disorder (ADHD) (Klingberg et al., 2002, 2005; Holmes et al., 2010).

Although these studies offer intriguing insights into the potentials of WM training, the diversity of training and transfer effects is still obscure. In other words, despite the vast amount of training literature, we are rather far away from a comprehensive understanding of the characteristics of cognitive functions which may benefit from WM training. The present study aimed to contribute to answering this question by systematically investigating, which cognitive improvements following WM training can transfer to other tasks and situations. In particular, we focused on executive control processes. To our knowledge, there exists no study that has specifically investigated transfer from WM training to executive functions. This is somewhat surprising, considering that executive functions are involved in the control and coordination of various sub-processes or tasks (e.g., Miyake et al., 2001). Due to the general nature of these functions, we suppose an involvement in a number of situations and tasks, for instance in the coordination of the performance of multiple tasks; in attention tasks that require either selective attention or attentional switches; as well as in tasks, such as comprehension and learning, that require activation of representations in long-term memory. Since WM is essential in the execution of all of these processes (e.g., Baddeley, 1996a), we assume that WM training affects beneficially performance also in tasks requiring such functions.

We trained participants on a task that has recently been shown to improve performance in tests of Gf, namely the dual *n*-back (Jaeggi et al., 2008, 2010). The dual *n*-back task is an inherently complex task that taps various executive processes. This is because it consists of two *n*-back tasks—a visuospatial (VS) and an auditory-verbal (AV) one—and they have to be performed simultaneously. An *n*-back task alone requires diverse executive processes, such as WM updating, monitoring of ongoing performance, and inhibition of irrelevant items. In the dual *n*-back, the presentation of two *n*-back tasks in different modalities calls for yet additional processes, such as dividing of attentional resources and managing the performance of two simultaneous tasks (Jaeggi et al., 2008). Accordingly, training on the dual *n*-back could presumably have separable, advantageous effects on the different executive functions it engages. Another crucial component of the task is that it is adaptive; that is, the level of difficulty is constantly adjusted according to each individual's performance. As a consequence, the development of task specific strategies is minimized, which is a prerequisite in training WM processes as such, independent of the trained material (Klingberg et al., 2002, 2005; Jaeggi et al., 2008).

We specified four executive functions that seem to correspond to particular requirements of the dual *n*-back, and investigated transfer effects from training to tasks measuring these four processes separately. First, the *n*-back task taxes WM updating processes: while new, relevant stimuli have to be coded into WM, old, irrelevant items have to be replaced (Morris and Jones, 1990; Miyake et al., 2000). In accordance with the dual modality nature of the training paradigm, we included three WM updating tasks: an AV task, a VS task, and a dual-modality task involving both AV and VS items. All tasks included stimulus sequences of varying lengths, and after each sequence participants had to reproduce the four last presented items of the sequence in the correct order. As it cannot be anticipated by the participants at which point the four last items have to be reported, this task requires continuous updating of WM contents. Previous studies have already reported increases in the amount of correctly reported item sequences following training on similar updating tasks, as well as transfer effects to an *n*-back task (Dahlin et al., 2008a,b). Therefore, we tested whether participants would show improvements in a WM updating task following training on the dual *n*-back task.

Second, a key feature of the dual *n*-back is the requirement to coordinate the concurrent performance of two tasks. To investigate whether training-related improved coordination of performing two simultaneous tasks would generalize beyond the training task, our second transfer task required dual-task performance; although with a reduced WM load as compared with our training task. Generally, executing two simultaneous tasks leads to increases in reaction times (RTs) and error rates, in contrast to a situation in which only one task has to be performed. In speeded choice RT tasks, these dual-task costs are assumed to be the consequence of capacity-limited task processes (e.g., central response selection), which prevent the concurrent performance of two temporally overlapping tasks. In situations of the psychological refractory period (PRP) type, performance of two temporally overlapping tasks varies as a function of the interval between the two tasks [stimulus onset asynchrony (SOA)]. Dual-task costs occur mainly in the second task so, that the shorter the SOA, the more the reaction to the second task is delayed (Pashler, 1994; Schubert, 1999). Training the performance of two concurrent tasks has been shown to improve dual-task performance as indicated by reduced dual-task costs. Among others, these studies have reported that practice can decrease dual-task costs by improving task coordination skills (Liepelt et al., 2011; Strobach et al., 2012a, in press). In the present dual-task paradigm of the PRP type, in each trial first an auditory and then a visual discrimination task was presented, with varying SOAs between these tasks. Participants responded to both tasks in the order of presentation as fast and as correctly as possible. Considering the demand of our training task to simultaneously perform two tasks tapping two different modalities, we investigated, whether dual-task costs would decrease in a multimodal dual-task of the PRP type following dual *n*-back training.

Alternatively, one could assume that the type of dual-task coordination skills are different in the dual *n*-back and the PRP-paradigm: while the dual *n*-back task requires the correct performance of two simultaneous tasks in WM, in the PRP-paradigm the emphasis is on RTs when performing two tasks that are separated by a varying interval. Thus, it is possible that the dual-task coordination skills that consist of successful coordination of two simultaneous tasks within WM, and that are gained in dual *n*-back training, do not manifest as improvements in the PRP-task, which on its part indicates the speed of processing two tasks.

Third, simultaneous performance of both *n*-back tasks requires rapid switching between the two task streams. Typically task switching leads to longer RTs compared with situations in which the same task is repeated. This delay is explained by task-set reconfiguration processes that need to take place before the execution of the next task (Rogers and Monsell, 1995; Monsell, 2003). However, previous research has shown that task-switch abilities can be improved by training (Minear and Shah, 2008; Karbach and Kray, 2009; Strobach et al., 2012a,b). To investigate, whether improved task-switching abilities gained after training on the dual *n*-back would transfer to task-switch performance, we included a transfer task that taps task switching processes. This paradigm comprises two tasks: letter categorization and digit categorization (Rogers and Monsell, 1995). In every trial, a stimulus pair consisting of a letter and a digit is presented and the participant has to perform either one of the categorization tasks so that in every other trial the tasks switch. In this way, switch and repetition trials alternate in these so-called mixed blocks. Performance in task switching situations can be measured in different ways, depending on what processes one is interested in. Sustained control processes—including maintaining task-set information and selecting between two tasks—are reflected in mixing costs. These are acquired by comparing performance in the repetition trials of mixed blocks with performance in trials of single-task blocks (i.e., blocks in which only one of the tasks is completed through the whole block), (Meiran et al., 2000). The flexibility of task-switching abilities is indicated by switch costs, which are attained by contrasting switch trials with repetition trials within mixed blocks. Consistent with the requirement in the dual *n*-back to both maintain task information of two different tasks and to switch between the tasks, we tested whether there would be a transfer effect to the mixing and/or switch costs in a task switching paradigm following training.

Fourth, training on the dual *n*-back task engages attention processes. Specifically, it requires continuous switching of attention between items in WM, so that when attending to a new item, attention is detached from an old, irrelevant item. These operations require efficient control of attention under strong time pressure. A typical finding in studies of the temporal distribution of attentional resources is the attentional blink (AB). When two targets are presented in a rapid serial visual presentation (RSVP) stream, separated by a temporal interval between 200 and 500 ms, the detection of the second target (T2) is impaired, thus, attention "blinks." It is not clearly established yet what causes the blink, but several models emphasize the role of central capacity limitations for the occurrence of the AB: attentional resources are depleted by the processing of the first target (T1), thus causing a deterioration in the processing of T2 (Shapiro et al., 1994; Chun and Potter, 1995; Jolicœur, 1998; Dux and Harris, 2007). However, the AB is not insensitive to training effects, as reported in a study by Slagter and colleagues (2007). In their experiment, participants attended three-month meditation training, after which an improvement in T2 detection was observed, that is, a decrease in the AB. In the present study, we hypothesized that the demands of the dual *n*-back may lead to an increase in attentional control by improving the abilities to distribute attentional resources. In accordance with the dual-modality nature of our training task, we included a cross-modal AB paradigm, which consists of two concurrently presented rapid serial presentation streams: a visual and an auditory one (Arnell and Jolicœur, 1999). There are two targets presented in each stream and the targets are separated by either a short or a long lag. Participants are required to detect the visual T1 and the auditory T2. We investigated whether there would be a change after training from pre- to post-test in correct T2 reports at the short lag, therefore, implicating a decrease in the magnitude of the AB.

Finally, we tested the hypothesis that WM training leads to increases in Gf. This is because up to date, evidence concerning the intriguing hypothesis of improving Gf by WM training has been inconclusive: some studies have reported improvements in reasoning tests following WM training (Klingberg et al., 2002, 2005; Olesen et al., 2004), while others have failed to show such transfer (Dahlin et al., 2008a; Thorell et al., 2009; Chein and Morrison, 2010). We administered the Raven's Advanced Progressive Matrices (RAPM) test, which is a classical measure of reasoning skills (Raven, 1990). We expected that, in line with the findings of Jaeggi and colleagues (2008), participants attending extensive and demanding WM training would score higher in the RAPM after training than before it, compared with their untrained counterparts. This assumption is plausible given that we provide a similar amount of training as provided to groups with increased scores after training in the reasoning task of Jaeggi and colleagues (2008).

There are several ways in which the transfer effects could arise. For example, transfer could occur when the training task and the transfer task engage shared processes of a single skill. For instance, Dahlin and colleagues (2008a) showed transfer from WM updating training to a 3-back task but not to other cognitive measures. Since both the training and the *n*-back task required continuous updating of WM contents, the authors inferred that the sharing of this process by the two tasks enabled the transfer effect. Along these lines, improvements gained via dual *n*-back training should be observed also in tasks that tap the respective executive functions involved in the dual *n*-back. On the other hand, it is possible that the training task affects a relevant domain-general mechanism that underlies both the training and the transfer tasks. Evidence in favor of this account was recently provided by Chein and Morrison (2010), who showed transfer from WM training to a broader scope of cognitive processes. They administered four weeks of training on complex verbal and spatial WM tasks taxing several different processes, such as encoding, attention, and WM updating. After training, improvements were demonstrated in other WM tasks as well as in cognitive control and complex reading comprehension tasks. Since training affected inherently different abilities, Chein and Morrison inferred that the training task must have affected a domain-general mechanism. The authors proposed that such a mechanism is likely to be responsible for attentional control processes that coordinate the maintenance of WM contents, irrespective of their modalities (verbal vs. spatial). Such a domain-general mechanism could comparably be affected by dual *n*-back training. Together, this is suggestive for transfer effects in the current study, although it remains open, whether such transfer would emerge for each of the applied transfer tasks given the differences in the underlying executive functions.

In summary, the present study set out to investigate, whether training effects from the dual *n*-back transfers to (1) a WM updating task, (2) dual-tasks with different demands on WM updating, (3) task switching, and (4) an AB task. Additionally, transfer to reasoning abilities was tested. Participants in the training group trained on the dual *n*-back task for 14 days, before and after which they attended pre- and post-tests on the training task as well as the five transfer tasks. In order to rule out mere retest effects, performance of the training group in each task was contrasted with the performance of a control group that underwent no training, but had a temporal interval between the pre- and post-tests equivalent in length to the training period of the training group. We are aware of the possible problems which may be related to the issue of an inactive control group, and these will be addressed in the discussion.

MATERIALS AND METHODS

SUBJECTS

Altogether 38 university students were recruited via announcements on notice boards at the psychology department of the Ludwig-Maximilians-University (LMU) Munich. They were randomly placed into two groups. While 20 participants (five male, mean age 24.4 years, two left-handed) took part in the training program, 18 participants (four male, mean age 24.5 years, two left-handed) were assigned to a control group that did not attend training; these group sizes exceeded the size in most of the trainings studies included in a recent review in the field of cognitive training (Morrison and Chein, 2011). Participants in both groups were equally rewarded with a monetary compensation of €8 per hour and all had normal or corrected-to-normal vision.

DESIGN AND PROCEDURE

In the beginning, all participants completed the four transfer tasks as well as the dual n-back task. For the next three weeks, the training group attended 14 daily training sessions (excluding weekends) on the dual n-back, while the control group underwent no training. After approximately three weeks from the first assessments, all participants attended a post-test on the dual n-back task and on the four transfer tasks. Additionally, in the beginning, all participants attended a pre-test session on the RAPM. However, only 13 participants from the training group and nine participants from the control group were available for a RAPM post-test. All tasks, except for the RAPM, were computerized and all tasks were performed in a laboratory. During the dual n-back sessions as well as in the RAPM pre- and post-tests, several participants could complete the tasks at the same time; while for the other tasks, only one participant at a time was tested. In all computerized tasks, except for task switching, responses were given on a German standard computer keyboard (QWERTZ).

MATERIALS

Training task

Our training task, the dual n-back[1], utilized the material described by Jaeggi and colleagues (2007), including simultaneously presented AV and VS stimuli (**Figure 1**). The AV stimuli consisted of eight German consonants (C, G, H, K, P, Q, T, and W) spoken in random order via headphones. The VS stimuli were blue squares presented one by one on a black background, randomly in eight possible locations. All stimuli were presented for 500 ms, and the interstimulus interval (ISI) was 2500 ms, thus resulting in a stimulus presentation rate of 3 s. A white fixation cross was present throughout each run. Participants reacted by pressing the key "A" with their left index finger for the VS task (i.e., match of square position in the present and n-back trial) and the key "L" with their right index finger for the AV task (i.e., match of consonant in the present and n-back trial). A new run was commenced by pressing the space-bar. Each run started with instructions about the level of n in the upcoming run, and ended with feedback of the participant's performance in the preceding run. The level of n was always the same in both tasks, with each training session starting from level $n = 2$. For each consecutive run, the n-back level was automatically adjusted so, that if the participant had at least 90% correct in both modalities in the previous run, the level of n in the next run was increased by one. But, if the participant had at most 70% correct in either of the modalities, the

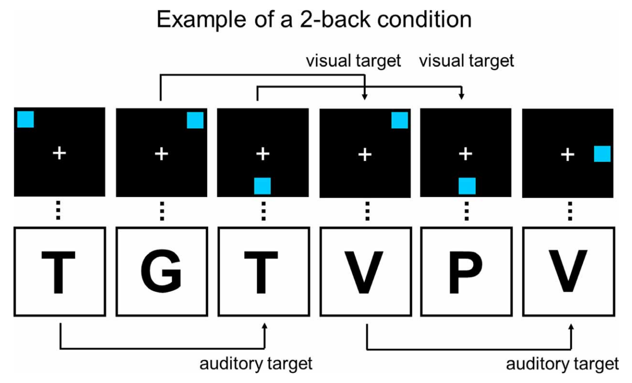

FIGURE 1 | Example of a 2-back condition in the dual *n*-back task that was used as the training task. The visual and auditory stimuli are presented simultaneously at identical rates. Figure adapted from Buschkuehl and colleagues (2007).

level of n was decreased by one in the next run, with the minimum level always being $n = 1$. In other cases the n-level stayed constant between successive runs. Altogether, 20 runs were completed in each session, and one run consisted of $20 + n$ trials (e.g., a 2-back task contained 22 trials). The dependent measure was the mean n-back level achieved during a training session.

Transfer tasks

Updating. This task included AV and VS stimuli. The AV stimuli consisted of the numbers 1, 2, 3, and 4, spoken in German and presented through headphones. The VS stimuli were black bars that appeared one by one in four different locations on the vertical axis of a computer screen. All stimuli were presented for 2000 ms with an ISI of 1000 ms. Each trial included a list of sequentially presented stimuli, and the list lengths were 5, 7, 9, 11, 13, and 15 items. On the presentation of the digits 1, 2, 3, and 4 in the AV task, participants responded by pressing the keys "Y", "X", "C", and "V" with the little, ring, middle, and index fingers of the left hand, respectively. In the VS task, responses were given using the right hand. Participants pressed the key "." with the little finger for a bar presented in the uppermost part of the screen, the "," key with the ring finger for a bar presented slightly above the middle of the screen, the "M" key with the middle finger for a bar presented slightly below the middle of the screen, and the "N" key with the index finger for a bar presented in the lowermost part of the screen. Altogether three blocks of 10 trials each were completed. The first block contained only AV stimuli, the second block only VS stimuli, and in the last block the AV and the VS stimuli were presented simultaneously. In the first two blocks, immediately following the presentation of a list, participants were asked to report the four last presented items of that list in the correct order. In the third block the task was the same; however, it was randomly required to reproduce either the last four AV or the last four VS items (the respective correct modality was indicated in the request presented after each sequence, i.e., "Please report the four last positions" or "Please report the four last digits"). In each task, participants were instructed to constantly update the four last items during the presentation of the lists. No speeded

[1]The dual n-back program is part of the software Brain Twister (Buschkuehl et al., 2007).

responses were required, but the participants were informed that a new list would start automatically after a fixed period of time (6000 ms) following the question about the last four presented items. Here, the outcome measure was the number of correctly reported four-item sequences, in each block separately.

Dual-task. The dual-task comprised two discrimination tasks. Task 1 was an auditory task in which participants had to react according to the pitch of a tone that was low (350 Hz), medium (950 Hz), or high (1650 Hz). Task 2 was a visual task in which participants were instructed to react according to the size of a triangle that was small (3.0° × 3.0°, of visual angle), medium (3.6° × 3.6°), or large (5.3° × 5.3°). Each trial started with the presentation of a white horizontal line in the middle of the screen, and it remained visible through the whole trial. Stimulus presentation followed 500 ms later. In the dual-task blocks, each trial started with the presentation of Task 1, followed by Task 2, and the SOA was randomly 50, 100, or 400 ms. In task instructions the correct order of responses (that is, first to Task 1, and then to Task 2) was emphasized. The intertrial interval (ITI) following correct trials was 1000 ms. After an erroneous response the word "Error" appeared on the screen for 1500 ms and the ITI was extended to 2500 ms. In the auditory task, responses were given with the left hand, by pressing the key "C" with the index finger, "X" with the middle finger, and "Y" with the ring finger for a low, medium, and high tone, respectively. The right hand was used for reactions in the visual task, by pressing "N" with the index finger, "M" with the middle finger, and "," with the ring finger for a large, medium-size, and small triangle, respectively. The whole experiment included five blocks, of which the first was a single-task block with Task 1 and the second was a single-task block with Task 2. Each of these blocks contained 45 trials. The last three blocks were dual-task blocks of 54 trials each. In all blocks participants were instructed to respond as fast and as correctly as possible. The RTs and error rates of Task 1 and Task 2 were used as the dependent measures.

Task switching. Each trial consisted of the presentation of a character pair including a digit that was either even (2, 4, 6, 8) or odd (3, 5, 7, 9) and a letter that was either a consonant (G, K, M, R) or a vowel (A, E, I, U). One pair at a time was presented in the center of a cell of a 2 × 2 grid. The first pair of each block appeared in the upper left cell, and the presentation of the following pairs moved always to the next cell clockwise. Each trial lasted until participant's response, or until 5000 ms had elapsed. The ITI was 150 ms; however, after an erroneous trial it was extended to 1500 ms and during this time also a tone of 30 ms in length was presented to indicate error. Participants were instructed to perform a number discrimination task (even vs. odd) and a letter discrimination task (consonant vs. vowel). They were asked to respond as fast and as correctly as possible with a response-box including two keys, by pressing the left key with the left index finger for even digits or consonants, and the right key with the right index finger for odd digits or vowels. Altogether six blocks of 48 trials each were completed. The first two blocks were single-task blocks: one letter categorization and one digit categorization block; and their order was counterbalanced across participants. The last four blocks were mixed blocks, in which both tasks had to be performed so that whenever the stimulus pair appeared in one of the upper cells of the grid, the digit categorization task was to be performed, and whenever the pair appeared in one of the lower cells of the grid, the participant had to perform the letter categorization task. Thus, half of the trials in these blocks were trials in which the same task was repeated from one trial to the next, and half were switch-trials in which the task switched. RT and error rates were used as outcome measures.

Attentional blink. This task included visual and auditory stimuli comprising letters of the alphabet (excluding N, X, C, and Y), and the digits 1, 2, 3, and 4. All visual items appeared sequentially in the same location in the middle of the screen. The auditory stimuli were presented through headphones. Each trial consisted of a concurrently presented visual and auditory stream. The lengths of the streams varied randomly, with one stream including 13, 15, 17, 19, or 21 items. Each stream consisted of mainly letters, except for two digits that appeared concurrently at two positions in the two modalities (i.e., simultaneous visual and auditory digits at position A and simultaneous visual and auditory digits at position B). The positions of the digits in the streams varied randomly, so that the first digits were presented at position 5, 7, 9, 11, or 13 and the second digits followed either three or six positions later. Each stimulus was presented for 80 ms, and with an ISI of 13 ms the presentation rate of the stimuli was 10.75 stimuli per second. Thus, the lag between the first and the second digit pair was either 279 ms or 558 ms. The first trial of a block was commenced by pressing the space-bar, and the following trials started automatically once the preceding trial had ended. In each trial, first a fixation cross was presented (500 ms), followed by a blank screen (500 ms), after which the auditory and the visual streams started simultaneously. At the end of each trial the participants were asked about the identities of the first visual digit (T1) and of the second auditory digit (T2). Responses were given with the right hand, using the number pad of a keyboard. Altogether two blocks with 40 trials each were completed. The critical outcome measure was the proportion of correctly identified T1 and T2.

RAPM. The RAPM consists of 36 test items, in each of which the task is to select a correct alternative among several possibilities to a matrix of patterns in which one pattern is missing. To enable the administration of the test two times (pre- and post-test)—meanwhile excluding test repetition effects—all participants performed in the pre-test either the odd numbered problems or the evenly numbered problems, and the other half in post-test (counterbalanced between participants). In both sessions, participants were given 20 min time to finish the test (i.e., half of the time of finishing the whole test as instructed in the test manual). The dependent measure was the number of correctly solved problems.

RESULTS

We first conducted a multivariate analysis of variance (MANOVA, Pillai's Trace) with Group (training vs. control) as a between-subject factor and Session (pre-test vs. post-test) as a within-subject factor on the data of each task as dependent variables (i.e., the mean level of n in the dual n-back, the number of correctly reported items in the WM updating task, RTs in Task 1 and Task 2 in the dual-task as well as in each trial type of task-switching, and the proportion of correct target identifications in the AB task). Since RTs were our primary measures in dual-task and in task-switching situations, we did not include the error rate data of these tasks in the MANOVA. This analysis yielded significant main effects of Group [$F_{(17, 54)} = 3.78$, $p < 0.001$, $\eta_p^2 = 0.54$] and Session [$F_{(17, 54)} = 3.32$, $p < 0.001$, $\eta_p^2 = 0.51$] as well as a significant Group × Session interaction [$F_{(17, 54)} = 3.39$, $p < 0.001$, $\eta_p^2 = 0.52$], which indicated that there were reliable group-specific performance changes from pre- to post-test. In the following we report the follow-up analyses for each task.

TRAINING TASK

Owing to technical problems, the data of two participants in the control group was lost (one male, one female), and thus, the analyses for the dual n-back task included the data of 16 control participants. A 2 (Group: training vs. control) × 2 (Session: pre-test vs. post-test) mixed-design analysis of variance (ANOVA) yielded main effects of Group [$F_{(1, 34)} = 29.18$, $p < 0.001$, $\eta_p^2 = 0.46$] and Session [$F_{(1, 34)} = 60.52$, $p < 0.001$, $\eta_p^2 = 0.64$], indicating that the trained group generally showed higher n-back levels ($M = 3.63$) than the control group ($M = 1.24$), and that the achieved mean n-back level at post-test ($M = 3.78$) was higher than that at pre-test ($M = 2.31$) across groups. Importantly, the Group × Session interaction was significant [$F_{(1, 34)} = 54.94$, $p < 0.001$, $\eta_p^2 = 0.62$], indicating a larger improvement of the training group than that of the control group (**Table 1**, **Figure 2**). This was confirmed by paired t-tests that showed a significant difference between the pre-test and post-test performances of the training group [$t_{(19)} = -8.70$, $p < 0.001$] and no such difference for the control group ($p > 0.44$). There was no difference between the performances of the two groups at pre-test ($p = 0.49$).

TRANSFER TASKS

Means and standard deviations in pre-test and in post-test, as well as effect sizes of the pre-test—post-test comparisons are presented in **Table 1** for each task, separately for the training group and the control group.

Table 1 | Pre- and post-test performance as well as the effect sizes for pre- and post-test comparisons of the training group and the control group in each transfer task.

Transfer task	Training group		*d*	Control group		*d*
	Pre-test	Post-test		Pre-test	Post-test	
Dual *n*-back	2.3 (0.4)	4.9 (1.5)	1.95	2.3 (0.5)	2.3 (0.5)	0.20
Updating performance in trials correct						
Auditory-verbal	4.7 (2.3)	6.3 (2.2)	0.56	4.1 (2.4)	5.4 (2.2)	0.53
Visuospatial	3.7 (2.2)	5.5 (2.2)	0.56	3.8 (2.7)	3.3 (2.7)	0.17
Dual-modality	1.9 (1.1)	2.3 (1.4)	0.27	1.4 (1.0)	2.3 (1.3)	0.64
Dual-task RTs in ms / error rates in %						
Task 1						
SOA 50	893 (217) / 11.3 (15.1)	820 (201) / 5.2 (4.7)	0.63	984 (201) / 10.5 (10.1)	913 (166) / 7.2 (8.3)	0.48
SOA 100	876 (215) / 10.1 (15.7)	812 (208) / 5.2 (5.3)	0.49	986 (210) / 8.6 (9.9)	899 (188) / 7.7 (9.1)	0.52
SOA 400	891 (209) / 9.2 (11.7)	829 (187) / 3.3 (3.6)	0.59	987 (189) / 8.4 (9.7)	940 (152) / 6.6 (10.3)	0.42
Task 2						
SOA 50	1,192 (213) / 8.0 (13.8)	1,097 (211) / 4.2 (3.9)	0.72	1,278 (221) / 7.7 (6.1)	1,147 (192) / 4.5 (3.7)	1.05
SOA 100	1,123 (216) / 9.3 (13.5)	1,029 (216) / 4.9 (5.1)	0.72	1,229 (224) / 5.5 (6.3)	1,091 (221) / 3.8 (3.2)	0.85
SOA 400	852 (183) / 7.8 (10.4)	763 (162) / 4.2 (3.5)	0.79	934 (194) / 5.1 (4.5)	819 (163) / 3.6 (3.3)	1.11
Task switching RTs in ms / error rates in %						
Switch trials	1,348 (279) / 8.8 (6.7)	1,155 (252) / 5.6 (4.5)	0.92	1,418 (225) / 9.4 (8.0)	1,278 (208) / 8.3 (6.0)	0.62
Repetition trials	877 (190) / 3.5 (5.3)	722 (141) / 2.3 (1.7)	1.61	847 (137) / 3.3 (6.3)	779 (132) / 2.9 (3.4)	0.79
Single-task trials	733 (85) / 3.9 (2.8)	672 (96) / 4.1 (3.9)	0.88	756 (135) / 6.1 (11.4)	705 (120) / 3.4 (2.4)	0.48
Attentional blink in % correct						
T1						
Short lag	85.9 (11.2)	89.8 (9.8)	0.35	76.4 (20.5)	83.8 (11.3)	0.46
Long lag	87.4 (12.8)	91.3 (12.9)	0.42	81.1 (19.4)	89.8 (11.4)	0.65
T2						
Short lag	45.5 (11.0)	56.0 (17.2)	0.87	42.7 (11.6)	44.3 (10.3)	0.14
Long lag	57.7 (16.8)	71.5 (16.4)	0.79	53.5 (20.3)	59.1 (16.9)	0.40
Raven's Advanced Progressive Matrices in number of correct tasks	13.9 (1.8)	13.7 (2.2)	0.07	9.0 (3.8)	10.9 (4.3)	1.23

Note: Values represent means (and standard deviations).

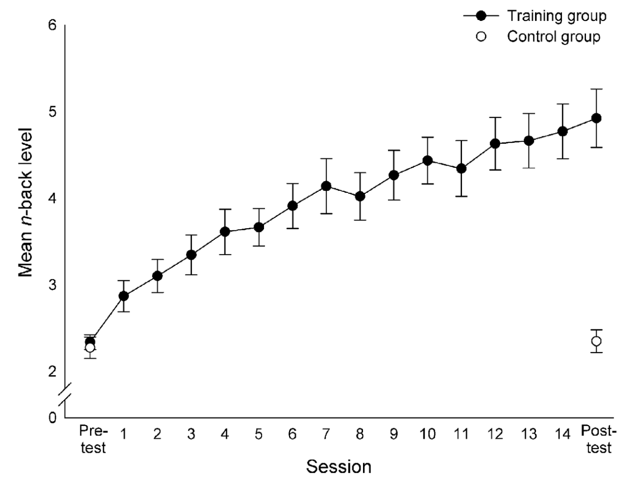

FIGURE 2 | Improvement in the performance of the training group through the training period and the performance of the control group in the pre- and post-tests in the dual *n*-back task. For each session, the mean *n*-back level is presented. Error bars indicate standard errors of the mean.

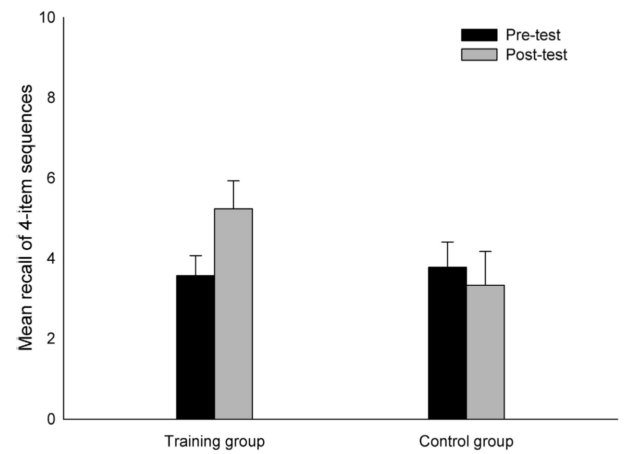

FIGURE 3 | The number of correctly reported four-item sequences in the VS updating task. Performance for both groups is illustrated separately for pre-test and post-test. Error bars indicate standard errors of the mean.

Updating

A 2 (Group: training vs. control) × 2 (Session: pre-test vs. post-test) × 3 (Block: AV vs. VS vs. dual-modality) mixed-design ANOVA conducted on the mean amount of correctly reported four-item sequences yielded a main effect of Session [$F_{(1, 36)} = 11.95$, $p < 0.005$, $\eta_p^2 = 0.25$], reflecting the fact that the participants reported more sequences correctly at post-test ($M = 4.21$) than at pre-test ($M = 3.27$). Also the main effect of Block was significant [$F_{(2, 72)} = 57.93$, $\eta_p^2 = 0.62$], which confirmed that the amount of correctly reported sequences varied between the three blocks (AV: $M = 5.11$; VS: $M = 4.08$; dual-modality: $M = 1.98$). The Group × Session × Block interaction reached significance [$F_{(2, 72)} = 3.60$, $p < 0.05$, $\eta_p^2 = 0.09$], suggesting that an interaction of Session and Block was modulated by the factor Group. Therefore, each block was separately submitted to two (Group: training vs. control) × 2 (Session: pre-test vs. post-test) ANOVAs. For the AV and dual-modality blocks, the Group × Session interaction was not significant (both p's > 0.3). However, for the VS block, this interaction was reliable [$F_{(1, 36)} = 5.48$, $p < 0.05$, $\eta_p^2 = 0.13$]. Bonferroni corrected paired t-tests conducted for the pre-test and post-test performances of the training and the control group confirmed that the trained participants showed an increase in the amount of correctly reported four-item sequences [$t_{(19)} = -2.49$, $p < 0.05$], while there was no difference for the control group between their pre- and post-test performances ($p > 0.48$) (**Figure 3**). Both groups did not differ with respect to their pre-test ($p = 0.80$), but differed regarding their post-test performance [$t_{(17)} = 3.02$, $p < 0.01$, Cohen's $d = 0.82$]. The main effect of Group and the remaining interactions were non-significant (all p's > 0.10). These results suggest that the trained participants improved in the VS updating task but not in the AV or the dual-modality task, and that the improvement of the training group in the VS task was not driven by differences in the groups' performances already at pre-test.

Dual-task

The RTs and error rates in Task 1 and in Task 2 were analysed separately with mixed-design 2 (Group: training vs. control) × 2 (Session: pre-test vs. post-test) × 3 (SOA: 50 ms vs. 100 ms vs. 400 ms) ANOVAs. For the RT analyses we excluded trials, in which an erroneous response was made to either one or both of the tasks.

Task 1. Participants were faster in post-test ($M = 866$ ms) than in pre-test ($M = 932$ ms), as confirmed by the significant main effect of Session [$F_{(1, 36)} = 13.15$, $p < 0.005$, $\eta_p^2 = 0.27$] in the RT analysis. The analysis of error rates revealed that participants made less errors in post-test ($M = 5.79\%$) than in pre-test ($M = 9.62\%$), as indicated by the significant main effect of Session [$F_{(1, 36)} = 6.33$, $p < 0.05$, $\eta_p^2 = 0.15$]. The main effect of SOA [$F_{(2,72)} = 3.97$, $p < 0.05$, $\eta_p^2 = 0.10$] revealed that the proportion of errors varied as a function of SOA (error rate for SOA 50 ms: $M = 8.44\%$; for SOA 100 ms: $M = 7.83\%$; and for SOA 400 ms: $M = 6.78\%$). No further main effect and no interaction reached significance in the Task 1 data (all p's > 0.10). These results indicate that both groups improved their performance from pre- to post-test equally; thus, there was no training-related improvement in Task 1 performance.

Task 2. A main effect of Session [$F_{(1, 36)} = 40.16$, $p < 0.001$, $\eta_p^2 = 0.53$] was obtained, indicating that the RTs in post-test ($M = 989$ ms) were significantly faster than in pre-test ($M = 1098$ ms). Additionally, the main effect of SOA was significant [$F_{(2, 72)} = 590.01$, $p < 0.001$, $\eta_p^2 = 0.94$], revealing the typical PRP effect in that the mean RTs decreased as the SOA increased (mean RT for SOA 50 ms: $M = 1177$ ms; for SOA 100 ms: $M = 1115$ ms; and for SOA 400 ms: $M = 838$ ms). The error rate analysis revealed a significant main effect of Session [$F_{(1, 36)} = 4.72$, $p < 0.05$, $\eta_p^2 = 0.12$], showing that more errors were made in pre-test ($M = 7.31\%$) than in post-test ($M = 4.18\%$). No other main effect and no interaction were significant in the Task 2 data (all p's > 0.07). The results of the error rate analyses are thus in concordance with the results of the RT as well as the Task 1 analyses, which showed an equal improvement for the training group and the control group from pre- to post-test, indicating that there was no training-related improvement in the dual-task performance.

Task switching

We conducted separate three-way mixed-design ANOVAs with factors Group, Session, and Trial type for analysing mixing costs and switch costs. In both analyses, the first two factors were identical (Group: training vs. control and Session: pre-test vs. post-test). In the analysis for mixing costs, the factor Trial type included data (RTs and error rates) from repetition trials vs. single-task trials; while in the analysis for switch costs, this factor included data (RTs and error rates) from switch trials vs. repetition trials. Due to an error in data acquisition, one participant in the training group had more than 87% incorrect responses on each trial type in the post-test, for which reason this subject's data was omitted from the task switching analyses. In the RT analyses of the remaining data, trials with incorrect responses (5.6% of trials) were excluded.

Mixing costs. We were interested in whether training affected sustained control processes, reflected as mixing costs in our task switching paradigm. The analysis on the mixing costs revealed a main effect of Session [$F_{(1, 35)} = 51.14$, $p < 0.001$, $\eta_p^2 = 0.59$], indicating faster RTs in post-test ($M = 719$ ms) than in pre-test ($M = 803$ ms). The RTs were also faster in single-task trials ($M = 716$ ms) than in repetition trials ($M = 806$ ms), [$F_{(1, 35)} = 28.12$, $p < 0.001$, $\eta_p^2 = 0.45$]. Furthermore, two interactions were significant. First, the reliable Group × Session interaction [$F_{(1, 35)} = 4.38$, $p < 0.05$, $\eta_p^2 = 0.11$] reflects the fact that the training group's improvement from pre-test to post-test was larger ($M = 108$ ms) than that of the control group ($M = 59$ ms). Second, and importantly, the three-way interaction Group × Session × Trial type was also significant [$F_{(1, 35)} = 4.55$, $p < 0.05$, $\eta_p^2 = 0.12$], which suggests that the group-specific improvement is differently expressed for different types of trials. Two further Group × Session ANOVAs were conducted separately on the RTs in single-task trials and repetition trials in order to investigate, which types of trials showed the stronger group-specific training effect. For the single-task trials, only the main effect of Session reached significance [$F_{(1, 35)} = 14.51$, $p < 0.001$, $\eta_p^2 = 0.29$], such that all participants improved from pre-test ($M = 744$ ms) to post-test ($M = 689$ ms). The analysis for the repetition trials revealed a reliable main effect of Session [$F_{(1, 35)} = 55.13$, $p < 0.001$, $\eta_p^2 = 0.61$] but, additionally, the Group × Session interaction reached significance [$F_{(1, 35)} = 8.52$, $p < 0.01$, $\eta_p^2 = 0.20$], confirming that the improvement of the training group from pre-test to post-test was larger ($M = 155$ ms) than that of the control group ($M = 68$ ms) (**Figure 4**). This indicates a greater improvement of the training group in mixing costs, compared with the control group. Other main effects or interactions or results from the analysis on error rates were not significant (all p's > 0.12).

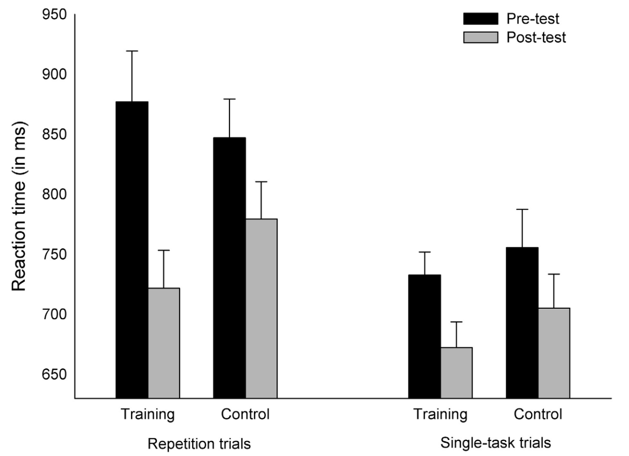

FIGURE 4 | Reaction times of the training and control groups in the repetition and single-task trials of the task switching experiment. Error bars indicate standard errors of the mean.

Switch costs. To investigate the effect of dual n-back training on the flexibility of task-switching abilities, we ran an analysis on the switch costs. This revealed a significant main effect of Session [$F_{(1, 35)} = 35.06$, $p < 0.001$, $\eta_p^2 = 0.50$], which indicated that the RTs were faster in post-test ($M = 984$ ms) than in pre-test ($M = 1123$ ms). Also the main effect of Trial type was significant [$F_{(1, 35)} = 306.80$, $p < 0.001$, $\eta_p^2 = 0.90$], indicating that the RTs in repetition trials ($M = 806$ ms) were faster than in switch trials ($M = 1300$ ms). An analysis for the error rates revealed only a significant main effect of Trial type [$F_{(1, 35)} = 98.96$, $p < 0.001$, $\eta_p^2 = 0.74$], indicating that the participants made more errors in switch trials ($M = 8.02\%$) than in repetition trials ($M = 2.99\%$). The other main effects and interactions were not significant (all p's > 0.06; for the important interaction Group × Session × Trial type $p = 0.54$), which indicates that the improvements from pre- to post-test were equal across both groups and that no group-specific transfer effects occurred for the switch costs.

Attentional blink

We performed 2 (Group: training vs. control) × 2 (Session: pre-test vs. post-test) × 2 (Lag: short vs. long) mixed-design ANOVAs separately for T1 and for T2 with the proportion of correctly identified targets.

T1

The analysis yielded a significant main effect of Session [$F_{(1, 36)} = 11.81$, $p < 0.005$, $\eta_p^2 = 0.25$], indicating that the participants identified T1 more often correctly in post-test ($M = 88.84\%$) than in pre-test ($M = 82.99\%$). Also the main effect of Lag reached significance [$F_{(1, 36)} = 9.37$, $p < 0.005$, $\eta_p^2 = 0.21$], indicating that T1 was more often correctly identified in the long lag ($M = 87.64\%$) than in the short lag ($M = 84.19\%$). The main effect of Group and the interactions did not reach significance (all p's > 0.09), thus showing that training had no effect on T1 identification.

T2

The means were calculated using only trials in which T1 was identified correctly. Significant main effects of Session [$F_{(1, 36)} = 20.76$, $p < 0.001$, $\eta_p^2 = 0.37$] and Lag [$F_{(1, 36)} = 70.93$, $p < 0.001$, $\eta_p^2 = 0.66$] revealed that the participants identified T2 better in post-test ($M = 58.03\%$) than in pre-test ($M = 50.03\%$) as well as in the long lag ($M = 60.73\%$) than in the short lag ($M = 47.33\%$). The Group × Session interaction was significant, as well [$F_{(1, 36)} = 6.14$, $p < 0.05$, $\eta_p^2 = 0.15$]. Follow-up analyses confirmed that the training group improved significantly in T2 identification from pre-test ($M = 51.60\%$) to post-test ($M = 63.73\%$) [$t_{(19)} = -5.04$, $p < 0.001$), while the control group performed equally well in both sessions ($p = 0.16$). Other main effects or interactions were not significant (all p's > 0.07). Since the group differences were not affected by Lag, it indicates that the improvement of the training group from pre-test to post-test was similar in both the long and the short lag (**Figure 5**). This suggests that the training group showed improvements in the identification of T2 across both lags.

Raven's Advanced Progressive Matrices (RAPM)

Performance scores of the participants who attended the RAPM-test in pre-test as well as in post-test were submitted to a 2 (Group: training vs. control) × 2 (Session: pre-test vs. post-test) mixed-design ANOVA. The training group gained higher scores ($M = 13.77$) than the control group ($M = 9.94$), [$F_{(1, 20)} = 9.69$, $p < 0.01$, $\eta_p^2 = 0.33$]. However, a significant Group × Session interaction [$F_{(1, 20)} = 5.25$, $p < 0.05$, $\eta_p^2 = 0.21$] indicated that these two groups differed to a different amount in the pre- and post-test sessions. While the training group showed higher scores than the control group in the pre-test session [$t_{(8)} = -3.69$, $p < 0.01$], this difference disappeared in the post-test session ($p > 0.8$). Probably, this finding can be attributed to a general ceiling effect in the training group, which performed very well in both the pre- and the post-test sessions. Therefore, due to its relatively low performance level in the pre-test session, the control group had more space for an improvement of the RAPM values in the post-test session, relative to the training group. In any case, we provided no evidence for WM transfer effects to the performance in the RAPM after training.

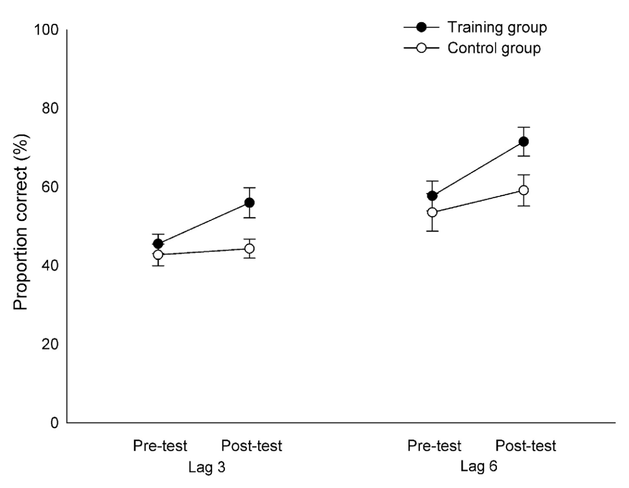

FIGURE 5 | Proportion of correctly reported T2|T1 for both lags in pre-test and in post-test for the training group and the control group. Error bars indicate standard errors of the mean.

DISCUSSION

The purpose of this study was to investigate, which improvements in executive control functions achieved through WM training can generalize beyond the training task and situation. Within three weeks of training with a demanding WM task, the dual *n*-back, participants improved their performance significantly from the first to the last session. A control group that did not undergo training, performed on an equal level in post-test as compared with its pre-test performance three weeks earlier. The improvement of the training group generalized to three untrained tasks: a VS WM updating task, task switching, and an AB task. Importantly, the improvement of the training group was confirmed by a MANOVA. There was no transfer to an AV WM updating task, to a dual-modality WM updating task and to a dual-task of the PRP type.

TRANSFER EFFECTS

The nearest transfer occurred to the VS WM updating task. Both the dual *n*-back and the updating task share the requirement to constantly update WM contents. However, there are crucial differences between the tasks that must be noted. First of all, there are dissimilarities between the stimuli of the two tasks (blue squares vs. black bars). Furthermore, the presentation time of the stimuli in the transfer task is different from that of the training task. Most importantly, the two tasks engage different processes: the *n*-back requires *recognition* of stimuli, whereas in the updating task correct stimuli have to be *recalled* from WM. With these aspects in mind, it can be concluded that the training paradigm indeed enhanced the ability to update WM contents, independent of the trained material. Interestingly, this transfer effect was only seen in the VS modality and spared the AV modality. There are two—not mutually exclusive—possibilities to explain this observation. Firstly, it is plausible that the auditory WM system is more rehearsed or automatized as a result of everyday auditory experiences, because remembering auditory information demands effective rehearsal processes (for example to understand speech) (Baddeley, 2003). Thus, there could be less space to improvement as compared with the visual WM, which for its part is not as strained in daily life (Baddeley, 1996b). According to our results, auditory WM updating is not insensitive to improvements related to task repetition, since we did see an improvement for both groups from pre-test to post-test in the AV WM updating task. But, to induce an effect of training on skill-level, a more demanding task than the current auditory part of the dual *n*-back task would probably be required. The second possibility is related to a theory posited by Miyake and colleagues (2001), according to which VS WM is more closely related to executive functioning (or, "the central executive") than verbal WM (see also Baddeley, 1996b). It might therefore be that the training task indeed rehearsed a central executive mechanism; but, since such mechanism is more closely tied to VS WM processes than to auditory ones, the current transfer effect was more pronounced in the VS updating task.

As for task switching, we found a transfer effect that was reflected in mixing costs but not in switching costs. It, therefore, seems that the transfer effect did not tap transient processes related to task switching (i.e., the ability to rapidly switch between performing two different tasks), but rather covered processes concerning sustained control (i.e., maintaining the two task sets in WM and in selecting appropriately between them when task performance is required). To calculate the magnitude of mixing costs, we compared performance in repetition trials to that in single-task trials. Even though these two trial types both require the performance of the same task from one trial to the next, they differ from each other in one critical aspect. In repetition trials, one has to maintain two task sets in WM, while in single-task trials only one task set is sufficient. The observation of a transfer effect on mixing costs (i.e., the difference between repetition and single-task trials) is therefore, nicely in accordance with the nature of the training task, which requires efficient control over the contents of WM. It is also congruent with the results from the WM updating task, in that an improvement in WM updating was observed only in the VS task and the stimuli in our task switching paradigm were also presented visually. With respect to switch costs, they have been described to be—at least partly—a measure of interference from the preceding task set (Allport et al., 1994; Mayr and Keele, 2000; Monsell, 2003; Kiesel et al., 2010). Thus, it is conceivable that our trained participants showed no reduction in switch costs since the training task did not encourage inhibiting one or the other task: participants were explicitly instructed that only successful performance of both the AV and the VS task would make them advance to the next *n*-level. Thus, concentrating on only one of the tasks and therefore having to inhibit the information from the other task would not have led to a performance improvement. This interpretation would to that end also be in accordance with the lack of transfer to the dual-modality updating task (see above), which in turn specifically required inhibition of the irrelevant task modality at the response phase.

Finally, we found a transfer effect to the AB task, such that T2 identification was improved after training. Also T1 accuracy improved from pre-test to post-test, excluding the possibility that the improvement in T2 identification was a sole consequence of the participants simply attending more to T2 at the expense of T1. Since our AB task tapped both the visual and the auditory modality, this is the first time that a training-related effect to a cross-modal AB task is shown; note that previous studies have shown effects only within the visual modality (Green and Bavelier, 2003; Slagter et al., 2007).

In the present study, participants showed an improvement in T2 accuracy in both the short and the long lag. Therefore, we cannot infer that there was a specific decrease in the trained participants' AB, but only that they could report T2 more correctly in general. However, a closer inspection of our data shows that participants still seemed to manifest an AB at the long lag (i.e., they detected T2 worse than T1 even though T2 followed T1 beyond the supposed AB time frame of 500 ms). In that event, it could be that our long lag may have not been long enough for the T2 to surpass the effect of AB. Assuming that the AB was indeed decreased and that we missed it because of the properties of our task, this finding would suggest that the improvement in temporal dividing of attentional resources was transferable beyond the training task. This would be in accordance with a previous study by Oberauer (2006), in which it was suggested that WM training (specifically on the *n*-back task) leads to a speed up in attentional processes within WM, rather than to a pure increase in WM capacity. Theories of AB generally address the magnitude of AB to be dependent on the amount of attentional capture by T1 and on the efficiency of T1 processing (Shapiro et al., 1997, 2006). It is thus possible that the improvement in the auditory T2 identification in our paradigm came about by a reduced limitation of T2 encoding due to an improvement in the processing of the *visual* T1. This would particularly be consistent with the already reported effects of transfer to tasks in the visual modality (i.e., the VS WM updating task and task switching). In fact, in a study by Slagter and colleagues (2007), a decreased AB after meditation training was explained by more efficient processing of T1. This was evident in their electrophysiological (EEG) data as a smaller P3b-component for T1 after training. As the P3b-component generally reflects the allocation of attentional resources, Slagter and colleagues suggested that meditation training improved the participants' control over the distribution of attentional resources: they were more efficient in deploying resources to T1, thus leading to an increased T2 accuracy. Consistent with our interpretation of improved division of attentional resources in time are also the findings by Green and Bavelier (2003). In their study, participants trained action video-game playing. Following training, the T2 accuracy was improved, such that the trained participants recovered faster than non-trainers from the effects of AB.

There is, however, another study by Boot and colleagues (2008) that did not find transfer after video-game training to AB. We believe that this discrepancy could be due to general differences between the studies. For example, the AB task itself was somewhat different between these studies. In the Boot and colleagues' study the task was to identify T1 and to detect whether T2 appeared or not; whereas in our study the task was to identify both T1 and T2, and T2 also appeared in every trial. Moreover, we used a cross-modal AB task, while Boot and colleagues' AB task was purely visual. It is thus possible that our AB task was more sensitive to the type of training we implemented. Yet another critical difference between these studies is that the collection of the transfer tasks in the study by Boot and colleagues was different from the present study: while in the former study participants performed 12 different tasks, in the latter study participants performed only four different tasks. Thus, it is possible that the larger number of transfer tasks in the study by Boot and colleagues, compared with the number of transfer tasks in the present study (four tasks) and in the study by Green and Bavelier (three tasks) counteracted a possible manifestation of transfer in the AB task. This would be consistent with findings of Schmeichel (2007), who has shown that engaging in one task including an executive function component can have a debilitating effect on the performance in other executive function tasks.

LACKING TRANSFER EFFECTS

Interestingly, training did not transfer to dual-task coordination skills, as revealed by a lack of training-related improvements in the PRP-paradigm. Although we initially expected an improvement in dual-task abilities following training, the observation of lacking transfer to the PRP-task may not be surprising for two reasons. First, a key element of the training task was indeed the demand to efficiently update WM contents, which was not essential for the transfer situation in the PRP dual-task. Second, the training task did not require speeded processing and execution of appropriate stimulus-response mappings, which is an essential characteristic for dual-task processing of the PRP task type (Schubert, 1999, 2008). Thus, the lack of commonalities between the dual-task processing in the trained dual *n*-back task and the transfer PRP dual-task situation may have avoided the appearance of specific transfer effects between both task situations.

We also found no transfer to Gf, as measured by the RAPM. This finding is consistent with the study by Jaeggi and colleagues (2008), which used the same training paradigm and found no transfer to the RAPM after eight sessions of training. However, another study by Jaeggi and colleagues (2010) did find transfer to RAPM after 20 sessions of dual *n*-back training. There is a critical difference between the ways how the RAPM were administered in the present study and in those other studies: Jaeggi and colleagues (2008, 2010) applied the test with a time restriction (20 min), whereas in our study the test was conducted according to the standardized procedure (Raven, 1990), which instructs to give participants a sufficient amount of time to finish the test. It seems plausible to explain the observation of a training-induced improvement of Gf in a speeded version of the RAPM by the proposed hypothesis that the current WM training optimizes specifically the efficiency of attentional processes within WM, as suggested in our AB results. Therefore, when the test is administered in line with the standardized procedure described in the test manual (as it was the case in the present study), potentially improved attentional processes may not decisively contribute to the performance level in the Gf test. As a consequence, the improvement in attentional processing does not reflect in the Gf level results of the current type of the RAPM test administration. It has already been suggested elsewhere, that the link between Gf and WM is a common attentional control mechanism (Gray et al., 2003; Kane et al., 2004; Halford et al., 2007), and in fact, Jaeggi and colleagues (2008) also included such views in their explanation for transfer from the dual *n*-back to measures of Gf. Other studies using a different WM training paradigm but that have administered the RAPM similarly to the present study (i.e., without time restrictions), have likewise not shown reliable transfer effects to Gf (Dahlin et al., 2008a; Chein and Morrison, 2010; Richmond et al., 2011), and thus our results support findings from these studies. In the present study, some participants were not available for the post-test on the RAPM. Thus, the sample size in this test was fairly small, and the lack of power might have contributed to the non-significant transfer effect. However, we applied a power analysis using G*Power (Faul et al., 2009), given α, power, and the effect size of our experiment to have an idea about whether a lack of power may explain lacking effects from pre- to post-test in the RAPM (see Faul et al., 2007, for critical issues with retrospective power analyses). Consistent with this idea, the present power analysis demonstrated that even the original sample size of 38 participants would not have been sufficient to lead to a significant training advantage from pre- to post-test.

Summarizing our results, we found transfer to a VS WM updating task, to a task switching situation as measured by mixing costs as well as to the AB task. The diversity of these transfer effects corresponds to the findings of Chein and Morrison (2010), who found transfer effects from a complex WM span task to a variety of other tasks, for example the Stroop-task and reading comprehension, and who proposed training of a domain-general mechanism as a prerequisite for transfer effects. The observations in the present study are also consistent with the assumption that cognitive enhancements from our training paradigm may have affected not only a specific but also a more domain-general mechanism involved in various executive processes. A strong candidate for such a more general mechanism would be, according to Chein and Morrison, the mechanism of attentional control. Attentional control processes are strongly present in all of the processes to which we observed transfer: in WM updating as detaching attention from irrelevant items and attending to new relevant items (similarly to our training task), in task switching mixing costs as the requirement to control attention between the two task sets (Braver et al., 2003), and finally in AB as the requirement to control the temporal dividing of attentional resources. Notably, regarding WM updating, we found transfer only to the VS task. This is worthy of mentioning in reference to theories, which propose that executive attentional mechanisms are more closely related to VS WM than auditory WM processes (Baddeley, 1996b; Miyake et al., 2001). Alternatively, it is possible, that our transfer effects were the consequence of improvements in the separate processes that were recruited by the training task and tapped by our transfer tasks. However, this approach would be problematic in explaining the lack of transfer to certain tasks and/or modalities, especially when one regards how small the differences between these distinct processes seem.

At last, there are certain limitations in the present study that should be acknowledged and discussed. In controlled cognitive training studies, one general practice has been to compare the performance of the training group to that of a control group, which does not attend any intervention (e.g., Olesen et al., 2004; Dahlin et al., 2008b; Jaeggi et al., 2008). In this way it has been possible to eliminate re-test effects; however, it is still questionable, to what degree performance changes of the training group can be attributed to the training task and not just to the existence of an intervention *per se* (Shipstead et al., 2010). In the current study we did not include an active control group, which might raise the question, how much of the performance improvements of the training group in the transfer tasks were due to our training paradigm and how much can be attributed to rather unspecific effects like e.g., the Hawthorne-effect (an improvement in a participants' performance caused by the sole awareness of being studied), to effects of motivation or simply to the engagement in a challenging and adaptive training task. Generally, we believe, that had the performance improvements been affected by these factors, we would have observed improvements across all tasks and situations. This was not the case in the present study. In fact, we demonstrated specific transfer effects (e.g., effects on repetition but not on single-task trials in task switching). Of course, one could argue that the transfer tasks were of different difficulty and, therefore, unspecific training effects could occur only in a subset of only the easiest tasks. However, this argument seems not to be valid, as, for example in the updating task, according to the amount of correctly reported sequences across both sessions and groups, the VS task was more difficult than the AV task, whereas the dual-modality task seemed to be the most difficult one. These observations are also supported by the comments of participants, who reported the VS task to have been more difficult than the AV task and the dual-modality task to have been the most difficult one. Therefore, if the transfer effect was driven by the easiness of the task, we should have observed improvements in the AV task rather than in the VS task. Similarly in the task switching paradigm, we observed transfer to the mixing costs, and this effect was driven by a group-specific improvement in the repetition trials compared with single-task trials, in which there was no training-related improvement. Considering that the RTs in the repetition trials were generally slower than the RTs in the single-task trials, it seems plausible that the repetition trials were more complex than the single-task trials. On the other hand, we found no transfer to switching costs, although the performance in the repetition and switch trials differed from each other significantly so that the RTs in switch trials were slower than the RTs in repetition trials. If the simplicity of the task underlay the transfer effect, our transfer effects in the task switching paradigm would seem counterintuitive. Based on this rather unsystematic pattern of transfer effects (from the perspective of task difficulty), we believe that the easiness or the simplicity of a transfer task does not determine transfer. Further, a study by Thorell and colleagues (2009) has shown that motivational factors as well as pure engagement in an intervention play a rather minor role in cognitive training, as in their study there were no differences in the performances of an active and a passive control group.

Apart from the methodological concerns about a no-contact control group, we would also emphasize that the inclusion of an active control group may not have been critical to the problem setting in our study. Our aim was to investigate transfer effects related to the dual *n*-back task without thoroughly specifying the components of the training that may underlie transfer.

Another issue pointed as questionable by Shipstead and colleagues (2010) is the inclusion of only a single task for each function. We recognize the problem with this approach, as it cannot be unambiguously concluded that there are improvements in a certain function, but rather in an aspect of a function as measured by a single task. With respect to the present study, we emphasize that first of all, on a general level, we investigated transfer effects from WM training to executive functions; and we used not only one but four different executive tasks for this purpose (WM updating, dual-task, task switching, AB). Second, although at first glance it would seem that for each executive function we implemented only one task, we would like to highlight that our transfer tasks did involve also overlapping processes. For example, WM updating is an essential process in our updating task as well as in task switching. Attentional control was required in the updating task, task switching, and in the AB task. Multitasking was relevant in the dual-task and in the dual-modality part of the updating task. Our results are also in accordance with these overlaps, in that we, for instance, found no transfer to either the dual-task or the dual-modality updating task.

The overlapping of processes between our transfer tasks aside, it should be kept in mind that in such comprehensive studies as the present one, one important criterion is not to exhaust the participants by bombarding them with an immense battery of tests. This assumption is consistent with (1) findings of Schmeichel (2007), who demonstrated effects of exhausting between executive tasks, and (2) the reduced transfer effects in a more exhausting post-test session including 12 transfer tasks (Boot et al., 2008), compared with a less exhausting test session including three transfer tasks (Green and Bavelier, 2003; see also Strobach et al., 2012a). We aimed to tap several executive functions, and encourage future studies to broaden the range of measurements in order to clarify the specific effects of WM training.

In sum, in the present study we have provided evidence that complex WM training can produce transfer effects to executive functions. Given the relative new field of training research and the contradictions in transfer findings, it is of great importance that future studies consistently aim at replicating the transfer effects found thus far in this and in previous training studies, with alterations in training and transfer tasks; as well as at investigating the crucial components and characteristics of successful training paradigms.

REFERENCES

Allport, A., Styles, E. A., and Hsieh, S. (1994). "Shifting intentional set: exploring the dynamic control of tasks," in *Attention and Performance XV: Conscious and Nonconscious Information Processing,* eds C. Umiltà and M. Moscovitch (Cambridge, MA: MIT Press), 421–452.

Arnell, K. M., and Jolicœur, P. (1999). The attentional blink across stimulus modalities: evidence for central processing limitations. *J. Exp. Psychol. Hum. Percept. Perform.* 25, 630–648.

Baddeley, A. (1996a). Exploring the central executive. *Q. J. Exp. Psychol. Sec. A* 49, 5–28.

Baddeley, A. (1996b). The fractionation of working memory. *Proc. Natl. Acad. Sci. U.S.A.* 93, 13468–13472.

Baddeley, A. (2003). Working memory: looking back and looking forward. *Nat. Rev. Neurosci.* 4, 829–839.

Barrouillet, P., and Lecas, J.-F. (1999). Mental models in conditional reasoning and working memory. *Think. Reasoning* 5, 289–302.

Bleckley, M. K., Durso, F. T., Crutchfield, J. M., Engle, R. W., and Khanna, M. M. (2003). Individual differences in working memory capacity predict visual attention allocation. *Psychon. Bull. Rev.* 10, 884–889.

Boot, W. R., Kramer, A. F., Simons, D. J., Fabiani, M., and Gratton, G. (2008). The effects of video game playing on attention, memory, and executive control. *Acta Psychol.* 129, 387–398.

Braver, T. S., Reynolds, J. R., and Donaldson, D. I. (2003). Neural mechanisms of transient and sustained cognitive control during task switching. *Neuron* 39, 713–726.

Buschkuehl, M., Jaeggi, S. M., Kobel, A., and Perrig, W. J. (2007). *BrainTwister - Aufgabensammlung für kognitives Training, Version 1.0.1. Manual und CD*. Bern: Institut für Psychologie, Universität Bern.

Chein, J. M., and Morrison, A. B. (2010). Expanding the mind's workspace: training and transfer effects with a complex working memory span task. *Psychon. Bull. Rev.* 17, 193–199.

Chun, M. M., and Potter, M. C. (1995). A two-stage model for multiple target detection in rapid serial visual presentation. *J. Exp. Psychol. Hum. Percept. Perform.* 21, 109–127.

Dahlin, E., Nyberg, L., Bäckman, L., and Stigsdotter Neely, A. (2008a). Plasticity of executive functioning in young and older adults: immediate training gains, transfer, and long-term maintenance. *Psychol. Aging* 23, 720–730.

Dahlin, E., Stigsdotter Neely, A., Larsson, A., Bäckman, L., and Nyberg, L. (2008b). Transfer of learning after updating training mediated by the striatum. *Science* 320, 1510–1512.

Daneman, M., and Carpenter, P. A. (1980). Individual differences in working memory and reading. *J. Verbal Learn. Verbal Behav.* 19, 450–466.

Dux, P. E., and Harris, I. M. (2007). On the failure of distractor inhibition in the attentional blink. *Psychon. Bull. Rev.* 14, 723–728.

Engle, R. W., Carullo, J. J., and Collins, K. W. (1991). Individual differences in working memory for comprehension and following directions. *J. Educ. Res.* 84, 253–262.

Engle, R. W., Kane, M. J., and Tuholski, S. W. (1999). "Individual differences in working memory capacity and what they tell us about controlled attention, general fluid intelligence, and functions of the prefrontal cortex," in: *Models of Working Memory: Mechanisms of Active Maintenance and Executive Control,* eds A. Miyake and P. Shah (Cambridge, MA: Cambridge University Press), 102–134.

Faul, F., Erdfelder, E., Buchner, A., and Lang, A.-G. (2009). Statistical power analyses using G*Power 3.1, tests for correlation and regression analyses. *Behav. Res. Methods* 41, 1149–1160.

Faul, F., Erdfelder, E., Lang, A.-G., and Buchner, A. (2007). G*Power 3, A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behav. Res. Methods* 39, 175–191.

Fry, A. F., and Hale, S. (1996). Processing speed, working memory, and fluid intelligence: evidence for a developmental cascade. *Psychol. Sci.* 7, 237–241.

Fukuda, K., and Vogel, E. K. (2009). Human variation in overriding attentional capture. *J. Neurosci.* 29, 8726–8733.

Gray, J. R., Chabris, C. F., and Braver, T. S. (2003). Neural mechanisms of general fluid intelligence. *Nat. Neurosci.* 6, 316–322.

Green, C. S., and Bavelier, D. (2003). Action video game modifies visual selective attention. *Nature* 423, 534–537.

Halford, G. S., Cowan, N., and Andrews, G. (2007). Separating cognitive capacity from knowledge: a new hypothesis. *Trends Cogn. Sci.* 11, 236–242.

Holmes, J., Gathercole, S. E., and Dunning, D. L. (2009). Adaptive training leads to sustained enhancement of poor working memory in children. *Dev. Sci.* 12, F9–F15.

Holmes, J., Gathercole, S. E., Place, M., Dunning, D. L., Hilton, K. A., and Elliott, J. G. (2010). Working memory deficits can be overcome: impacts of training and medication on working memory in children with ADHD. *Appl. Cogn. Psychol.* 24, 827–836.

Jaeggi, S. M., Buschkuehl, M., Etienne, A., Ozdoba, K., Perrig, W. J., and Nirkko, A. C. (2007). On how high performers keep cool brains in situations of cognitive overload. *Cogn. Affect. Behav. Neurosci.* 7, 75–89.

Jaeggi, S. M., Buschkuehl, M., Jonides, J., and Perrig, W. J. (2008). Improving fluid intelligence with training on working memory. *Proc. Natl. Acad. Sci. U.S.A.* 105, 6829–6833.

Jaeggi, S. M., Studer-Luethi, B., Buschkuehl, M., Su, Y.-F., Jonides, J., and Perrig, W. J. (2010). The relationship between n-back performance and matrix reasoning – implications for training and transfer. *Intelligence* 38, 625–635.

Jolicœur, P. (1998). Modulation of the attentional blink by on-line response selection: evidence from speeded and unspeeded Task1 decisions. *Mem. Cogn.* 26, 1014–1032.

Kane, M. J., Bleckley, M. K., Conway, A. R. A., and Engle, R. W. (2001). A controlled-attention view of working-memory capacity. *J. Exp. Psychol. Gen.* 130, 169–183.

Kane, M. J., Brown, L. H., Mcvay, J. C., Silvia, P. J., Myin-Germeya, I., and Kwapil, T. R. (2007). For whom the mind wanders, and when. *Psychol. Sci.* 18, 614–621.

Kane, M. J., Hambrick, D. Z., Tuholski, S. W., Wilhelm, O., Payne, T. W., and Engle, R. W. (2004). The generality of working memory capacity: a latent-variable approach to verbal and visuospatial memory span and reasoning. *J. Exp. Psychol. Gen.* 133, 189–217.

Karbach, J., and Kray, J. (2009). How useful is executive control training? Age differences in near and far transfer of task-switching training. *Dev. Sci.* 12, 978–990.

Kiesel, A., Steinhauser, M., Wendt, M., Falkenstein, M., Jost, K., Philipp, A. M., and Koch, I. (2010). Control and interference in task switching – a review. *Psychol. Bull.* 136, 849–874.

Klingberg, T., Fernell, E., Olesen, P. J., Johnson, M., Gustafsson, P., Dahlström, K., Gillberg, C. G., Forssberg, H., and Westerberg, H. (2005). Computerized training of working memory in children with ADHD – a randomized, controlled trial. *J. Am. Acad. Child Adolesc. Psychiatry* 44, 177–186.

Klingberg, T., Forssberg, H., and Westerberg, H. (2002). Training of working memory in children with ADHD. *J. Clin. Exp. Neuropsychol.* 24, 781–791.

Kyllonen, P. C., and Christal, R. E. (1990). Reasoning ability is (little more than) working-memory capacity? *Intelligence* 14, 389–433.

Liepelt, R., Strobach, T., Frensch, P., and Schubert, T. (2011). Improved intertask coordination after extensive dual-task practice. *Q. J. Exp. Psychol.* 64, 1251–1272.

Mayr, U., and Keele, S. W. (2000). Changing internal constraints on action: the role of backward inhibition. *J. Exp. Psychol. Gen.* 129, 4–26.

Meiran, N., Chorev, Z., and Sapir, A. (2000). Component processes in task switching. *Cogn. Psychol.* 41, 211–253.

Minear, M., and Shah, P. (2008). Training and transfer effects in task switching. *Mem. Cogn.* 36, 1470–1483.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., and Howerter, A. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: a latent variable analysis. *Cogn. Psychol.* 41, 49–100.

Miyake, A., Friedman, N. P., Rettinger, D. A., Shah, P., and Hegarty, M. (2001). How are visuospatial working memory, executive functioning, and spatial abilities related? A latent-variable analysis. *J. Exp. Psychol. Gen.* 130, 621–640.

Monsell, S. (2003). Task switching. *Trends Cogn. Sci.* 7, 134–140.

Morris, N., and Jones, D. M. (1990). Memory updating in working memory: the role of the central executive. *Br. J. Psychol.* 81, 111–121.

Morrison, A. B., and Chein, J. M. (2011). Does working memory training work? The promise and challenges of enhancing cognition by training working memory. *Psychon. Bull. Rev.* 18, 46–60.

Oberauer, K. (2006). Is the focus of attention in working memory expanded through practice? *J. Exp. Psychol. Learn. Mem. Cogn.* 32, 197–214.

Olesen, P. J., Westerberg, H., and Klingberg, T. (2004). Increased prefrontal and parietal activity after training of working memory. *Nat. Neurosci.* 7, 75–79.

Pashler, H. (1994). Dual-task interference in simple tasks: data and theory. *Psychol. Bull.* 116, 220–244.

Raven, J. C. (1990). *Advanced Progressive Matrices: Sets, I, II*. Oxford: Oxford University Press.

Richmond, L. L., Morrison, A. B., Chein, J. M., and Olson, I. R. (2011). Working memory training and transfer in older adults. *Psychol. Aging* 26, 813–822.

Rogers, R. D., and Monsell, S. (1995). Costs of a predictable switch between simple cognitive tasks. *J. Exp. Psychol. Gen.* 124, 207–231.

Schmeichel, B. J. (2007). Attention control, memory updating, and emotion regulation temporarily reduce the capacity for executive control. *J. Exp. Psychol. Gen.* 136, 241–255.

Schmiedek, F., Lövdén, M., and Lindenberger, U. (2010). Hundred days of cognitive training enhance broad cognitive abilities in adulthood: findings from the COGITO study. *Front. Aging Neurosci.* 2:27. doi: 10.3389/fnagi.2010.00027

Schubert, T. (1999). Processing differences between simple and choice reactions affect bottleneck localization in overlapping tasks. *J. Exp. Psychol. Hum. Percept. Perform.* 25, 408–425.

Schubert, T. (2008). The central attentional limitation and executive control. *Front. Biosci.* 13, 3569–3580. doi: 10.2741/2950

Shapiro, K. L., Arnell, K. M., and Raymond, J. E. (1997). The attentional blink. *Trends Cogn. Sci.* 1, 291–296.

Shapiro, K. L., Raymond, J. E., and Arnell, K. M. (1994). Attention to visual pattern information produces the attentional blink in rapid serial visual presentation. *J. Exp. Psychol. Hum. Percept. Perform.* 20, 357–371.

Shapiro, K. L., Schmitz, F., Martens, S., Hommel, B., and Schnitzler, A. (2006). Resource sharing in the attentional blink. *Neuroreport* 17, 163–166.

Shipstead, Z., Redick, T. S., and Engle, R. W. (2010). Does working memory training generalize? *Psychol. Belg.* 50, 245–276.

Slagter, H. A., Lutz, A., Greischar, L. L., Francis, A. D., Nieuwenhuis, S., Davis, J. M., and Davidson, R. J. (2007). Mental training affects distribution of limited brain resources. *PLoS Biol.* 5:e138. doi: 10.1371/journal.pbio.0050138.g001

Strobach, T., Frensch, P. A., and Schubert, T. (2012a). Video game practice optimizes executive control skills in dual-task and task switching situations. *Acta Psychol.* 140, 13–24.

Strobach, T., Frensch, P. A., Soutschek, A., and Schubert, T. (in press). Investigation on the improvement and transfer of dual-task coordination skills. *Psychol. Res.*

Strobach, T., Liepelt, R., Schubert, T., and Kiesel, A. (2012b). Task switching: effects of practice on switch and mixing costs. *Psychol. Res.* 76, 74–83.

Thorell, L. B., Lindqvist, S., Bergman Nutley, S., Bohlin, G., and Klingberg, T. (2009). Training and transfer effects of executive functions in preschool children. *Dev. Sci.* 12, 106–113.

Westerberg, H., Jacobaeus, H., Hirvikoski, T., Clevberger, P., Östensson, M. L., Bartfai, A., and Klingberg, T. (2007). Computerized working memory training after stroke – a pilot study. *Brain Inj.* 21, 21–29.

Westerberg, H., and Klingberg, T. (2007). Changes in cortical activity after training of working memory – a single-subject analysis. *Physiol. Behav.* 92, 186–192.

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The impact of auditory working memory training on the fronto-parietal working memory network

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Working memory training has been widely used to investigate working memory processes. We have shown previously that visual working memory benefits only from intra-modal visual but not from across-modal auditory working memory training. In the present functional magnetic resonance imaging study we examined whether auditory working memory processes can also be trained specifically and which training-induced activation changes accompany theses effects. It was investigated whether working memory training with strongly distinct auditory materials transfers exclusively to an auditory (intra-modal) working memory task or whether it generalizes to a (across-modal) visual working memory task. We used adaptive *n*-back training with tonal sequences and a passive control condition. The memory training led to a reliable training gain. Transfer effects were found for the (intra-modal) auditory but not for the (across-modal) visual transfer task. Training-induced activation decreases in the auditory transfer task were found in two regions in the right inferior frontal gyrus. These effects confirm our previous findings in the visual modality and extents intra-modal effects in the prefrontal cortex to the auditory modality. As the right inferior frontal gyrus is frequently found in maintaining modality-specific auditory information, these results might reflect increased neural efficiency in auditory working memory processes. Furthermore, task-unspecific (amodal) activation decreases in the visual and auditory transfer task were found in the right inferior parietal lobule and the superior portion of the right middle frontal gyrus reflecting less demand on general attentional control processes. These data are in good agreement with amodal activation decreases within the same brain regions on a visual transfer task reported previously.

Keywords: auditory, *n*-back task, training, visual, working memory, plasticity, fMRI

INTRODUCTION

The ability to keep representations in an active and accessible state is crucial for adaptive, intelligent behavior and is assumed to underlie a vast amount of cognitive functions such as language learning or problem solving (Baddeley, 1986, 2002, 2003). The temporary storage and manipulation of information has been termed working memory. One of the prominent working memory models, the multicomponent model (Baddeley and Hitch, 1974; Baddeley, 2002, 2003), suggests a system that comprises a central executive and subsystems specialized for maintaining specific types of information (Baddeley and Logie, 1999). The phonological loop stores auditory and phonological information and uses a subvocal rehearsal system to refresh information whereas the visual-spatial sketchpad is specialized for holding spatial and non-spatial visual information (e.g., Baddeley, 1986; Baddeley and Logie, 1999). Although the distinction between the two slave systems has triggered a considerable amount of research, the question to which degree these systems are plastic and trainable and whether training might affect the respective neural networks was rarely investigated.

This distinction between visual and auditory working memory systems can be found in several contemporary working memory models (e.g., Baddeley, 2003; Zimmer, 2008). However, most functional neuroimaging studies showed that across a wide variety of tasks such as the *n*-back task, item recognition or delayed matching tasks the bilateral fronto-parietal working memory network is active mainly independent of stimulus type (Nystrom et al., 2000; Wager and Smith, 2003; Owen et al., 2005). From these data it follows that a clear modality-specific dissociation for visual and auditory information might potentially not exist in the working memory network, which is constituted by direct and reciprocally connections between posterior brain regions including the intraparietal sulcus and posterior and mid-dorsolateral frontal brain regions (Petrides and Pandya, 2002; Mecklinger and Opitz, 2003).

Only a few studies have directly contrasted working memory for visual and auditory information. Studies using non-verbal visual and auditory material found subtle differences in the activity of the prefrontal cortex for information that differed in input modality. A working memory study by Rämä and Courtney (2005) with non-spatial visual (faces) and auditory materials (human voices) used a delayed recognition task and found subtle activation differences in the ventral prefrontal cortex: faces activated the dorsal part at Brodmann Area (BA) 44/45 more strongly than voices, while voices more strongly activated the inferior part at BA 45/47 of the ventral prefrontal cortex. These data provide evidence for a functional segregation within the ventral prefrontal cortex with ventral regions recruited by auditory and dorsal regions recruited by visual working memory processes. In a similar vein, Protzner and McIntosh (2007) compared auditorily and visually presented white noise bursts in simple working memory tasks *and* found modality-specific activations in the fronto-parietal network in addition to activations in sensory cortices. The auditory task version led to stronger activations in the right putamen and left posterior cingulate gyrus, while for the visual version stronger activations in the right middle frontal cortex, left middle cingulate, and left inferior parietal temporal cortex were found. Functional brain imaging studies using visually and auditorily presented verbal material also found modality-specific activation patterns (Crottaz-Herbette et al., 2004; Rodriguez-Jimenez et al., 2009). Both studies investigated working memory for auditorily and visually presented verbal stimuli, using digit numbers (Crottaz-Herbette et al., 2004) or letters (Rodriguez-Jimenez et al., 2009) and a 2-back task. They report greater activations for auditory material in the left dorsolateral prefrontal cortex, whereas the visual version of the task led to stronger activations in the left posterior parietal cortex (Rodriguez-Jimenez et al., 2009). However, these modality-specific dissociations need to be interpreted cautiously because by using verbal materials activations found for visual materials could actually represent phonological transformation processes rather than effects which are specific for processing visual input (Smith and Jonides, 1997; Baddeley et al., 1998; Suchan et al., 2006). Even though the studies examining the dissociation between holding auditory and visual information in working memory leave a rather inhomogeneous picture, most of the studies refer to a relative dissociation of modality-specific activity.

Functional brain imaging studies on auditory memory for pitch further specified the neural circuitry for auditory object working memory i.e., working memory for sound identity information (Zatorre et al., 1994; Griffiths et al., 1999; Gaab et al., 2003; Koelsch et al., 2009). Using different kinds of pitch working memory tasks activations in the right inferior frontal region (Zatorre et al., 1994; Griffiths et al., 1999) or the left inferior frontal gyrus (Gaab et al., 2003) were found besides more inhomogenous activations between the studies in the cerebellum, posterior temporal and parietal regions. Furthermore, Koelsch et al. (2009) found that rehearsal of either the pitch information or the verbal information of sung syllables activated the ventrolateral premotor cortex (encroaching Broca's area), dorsal premotor cortex, the planum temporale, inferior parietal lobule, the anterior insula as well as subcortical structures and the cerebellum. By this, rehearsal of tonal and verbal information seems to recruit strongly overlapping neural networks. Notably, although the results of the studies are not homogenous, all of them found activations in the prefrontal cortex especially the left or right inferior frontal cortex to be involved in working memory for melodic and pitch information. Together the functional brain imaging studies contrasting auditory vs. visual material and the studies on the neural correlates of auditory object working memory speak for a specific involvement of the inferior frontal gyri for holding and rehearsing auditory object information in working memory.

To examine the functional plasticity of holding specific information in working memory, few recent studies have employed working memory training (Sayala et al., 2006; Schneiders et al., 2011; see Lövdén et al., 2010, for a review). More precisely, they used this method to disentangle specific components or processes improved by the training. This aim is based on the idea that cognitive training leads to improvements only in those tasks which share processing components with the trained task and thus might involve similar or overlapping brain regions (Jonides, 2004; Dahlin et al., 2008; Jaeggi et al., 2008; Lövdén et al., 2010; Morrison and Chein, 2011). From this commonality logic it follows that one approach to investigate trained processes is to compare two (or more) training tasks, which differ only in terms of a processing component of interest (Lövdén et al., 2010; Schneiders et al., 2011). This approach will be referred to as "training-specificity approach" in the following because multiple training regimens are compared with respect to the differential effects they have on one and the same transfer task. Another approach is to investigate the degree to which one specific training regime results in improved performance on multiple transfer tasks which do or do not share the processing component of interest (for a similar approach see Dahlin et al., 2008). Thus, if the training was effective and in turn the processing component of the training task improved, transfer effects should be found only for those transfer tasks, which engage that process. In the following this approach is referred to as "task-specificity approach."

In a previous training study we applied the "training-specificity approach" to investigate the impact of intra-modal and across-modal working memory training on a visual working memory task (Schneiders et al., 2011). Larger improvements after visual working memory training compared to auditory or no training were found in a visual 2-back task with abstract black and white pattern stimuli. These intra-modal effects were accompanied by training-related decreases in activation in the right middle frontal gyrus at BA 9 resulting from visual training only. Both trainings—in the visual and auditory modality—led to decreased activation in the superior portion of the right middle frontal gyrus at BA 6 and the right posterior parietal lobule at BA 40. These results support the view that working memory for visual materials can be trained separately from auditory materials and leads to increased neural efficiency i.e., reduced brain activation in combination with better performance in the visual 2-back task after visual training. This effect can functionally be dissociated from amodal activation decreases which were present after both, visual and auditory training at BA 6 and BA 40. These effects were taken to reflect more effective general control processes. Together these data could convincingly demonstrate that intra-modal training effects occur on the behavioral and neural level in the visual modality. As there was no auditory transfer task in our previous study, the data do not speak to the question whether working memory is also trainable specifically for auditory material.

The aim of the present study was to investigate whether auditory working memory training (training task) leads to specific improvements in the intra-modal auditory modality (near transfer task) or to general (across-modal) improvements also in visual working memory (far transfer tasks). By this we follow the task-specificity approach of using one training regimen to elucidate the nature of plasticity for holding specific types of information in working memory. To increase the likelihood of obtaining training gains in auditory working memory, we used highly salient tonal sequences in an auditory adaptive *n*-back training paradigm, in which the global pitch contour pattern, i.e., the relative pitch of tones in a sequence, had to be compared to the pattern presented *n* positions back in the stimulus train. As it was already shown that such pitch contour discrimination can be trained (Foxton et al., 2004), we assume that this stimulus material is highly suitable to train holding and rehearsing auditory information in working memory. Similarly to what we already demonstrated for the visual modality (Schneiders et al., 2011), it was hypothesized that working memory is specifically trainable for auditory material and thus its training results in considerable improvements in an intra-modal working memory task (near transfer effects) whereas more far transfer effects on a visual working memory task should be absent or decidedly smaller.

Additionally, we examined whether intra-modal and across-modal transfer effects of auditory working memory training are accompanied by differential activation changes in the fronto-parietal working memory network. Previous studies reported a great variety of activation patterns resulting from cognitive training (e.g., Jonides, 2004; Kelly and Garavan, 2005; Kelly et al., 2006; Buschkuehl et al., 2012). First, activation decreases in the same brain areas before and after training were consistently reported in studies using short-term working memory training (within-session practice) (Garavan et al., 2000; Jansma et al., 2001; Landau et al., 2004; Sayala et al., 2006). This pattern was usually taken to reflect more efficient processing in task-specific brain areas as a consequence of training. However, studies using more prolonged working memory training over several separate sessions exhibited a more inconsistent pattern of results. Most of the studies found activation decreases in the fronto-parietal working memory network (Olesen et al., 2004; Dahlin et al., 2008; Schneiders et al., 2011). Some studies additionally (Olesen et al., 2004; Dahlin et al., 2008) or exclusively (Jolles et al., 2010) report activation increases in brain regions that were active before and after training which are usually taken as an expansion of neural structures involved in the processing of the task. Furthermore, Hempel et al. (2004) report a combination of both patterns, i.e., an inverted u-shaped function of activation changes during training of an *n*-back working memory task. According to Kelly and Garavan (2005) different patterns of brain activity within the same areas before and after working memory training are referred to as redistribution and are taken to reflect a combination of *more efficient engagement of task-specific cognitive processes and* reduced demands on attentional control processes as a function of training. Particularly, prefrontal cortex, anterior cingulate, and posterior parietal cortex are assumed to fulfill such a "scaffolding" function that becomes redundant after extensive practice. Those "scaffolding" areas broadly overlap with the common fronto-parietal working memory network.

Another pattern of training-related changes in brain activation, namely the activation of new brain areas after training, has been termed reorganization and is assumed to lead to a qualitative change in the processes used to solve the trained task (Kelly and Garavan, 2005; Kelly et al., 2006). Although this pattern of results is commonly found in various cognitive training studies (e.g., Poldrack et al., 1998; Poldrack and Gabrieli, 2001; Erickson et al., 2007) to our knowledge, there is no single study reporting such a pattern of activation change as a result of working memory training.

Although activation increases in fronto-parietal brain regions are the most frequent activation changes after working memory training, there is still some inconsistency in the literature on the nature of neural activation changes after working memory training. Consistent with a number of studies mentioned above, we assume that within the prefrontal cortex, there exists a relative specialization for auditory object working memory with the ventrolateral prefrontal cortex being involved in auditory working memory tasks (for a review see also Rämä, 2008). Thus, this region might be recruited for maintaining and rehearsing auditory material over short periods of time. Auditory working memory training should therefore enhance the processing efficiency in this region, as indicated by activation decreases in an auditory but not a visual working memory task as well as behavioral improvements specifically in the auditory task.

Activation changes in a visual working memory task after auditory working memory training should be found in more posterior regions of the fronto-parietal working memory network, which are commonly recruited by amodal control and attentional processes in working memory tasks and for which activation decreases after *n*-back working memory training have been reported independently of training modality and behavioral improvements (Schneiders et al., 2011). The latter prediction is based on the assumption that the posterior parietal cortex reflects training-unspecific (Schneiders et al., 2011) and task-unspecific effects (present study) to a similar extent.

MATERIALS AND METHODS

PARTICIPANTS AND PROCEDURE

Thirty-two undergraduate students of Southwest University, Chongqing, China, 17 females and 15 males, mean age = 21.31 years (age range = 18–24 years), participated in this study. All participants were right-handed as assessed by the Edinburgh Inventory (Oldfield, 1971) and indicated on a screening form to be physically and psychologically healthy, to have normal hearing and normal or corrected to normal vision. Subjects were unselected for musical training: most of them had received some musical instruction as part of their elementary or high school education, but none were professional musicians or had more than five years of learning to play an instrument. They gave written informed consent before testing and received 10 Yuan/h for their participation.

As shown in **Figure 1** participants were assigned to either the auditory training group ($n = 16$) (mean age = 21.13 years, age range = 18–14 years) or the no training control group (mean age = 21.50 years, age range = 19–23 years). The groups were matched according to age ($p = 0.43$), gender ($p = 0.73$), fluid intelligence as measured by the Bochumer Matrizentest (BOMAT) (Hossiep et al., 1999) ($p = 0.60$).

Before training, participants took part in an initial fMRI pretest. The training group received eight training sessions within two weeks following the initial fMRI pretest. During the training participants performed an auditory adaptive *n*-back task with tonal sequences. Twenty-one to 22 days after the initial fMRI pretest all participants participated in the fMRI posttest.

TASKS

TRAINING TASK

To train auditory working memory, we used an adaptive *n*-back paradigm adapted from Jaeggi et al. (2008) (see **Figure 2**). In the *n*-back task, a sequence of stimuli is presented consecutively. It has to be decided whether the present stimulus matches the stimulus that was presented *n* positions back in the sequence. Stimuli were presented sequentially at a rate of 3700 ms (stimulus length = 700 ms, inter-stimulus interval = 3000 ms). Each block

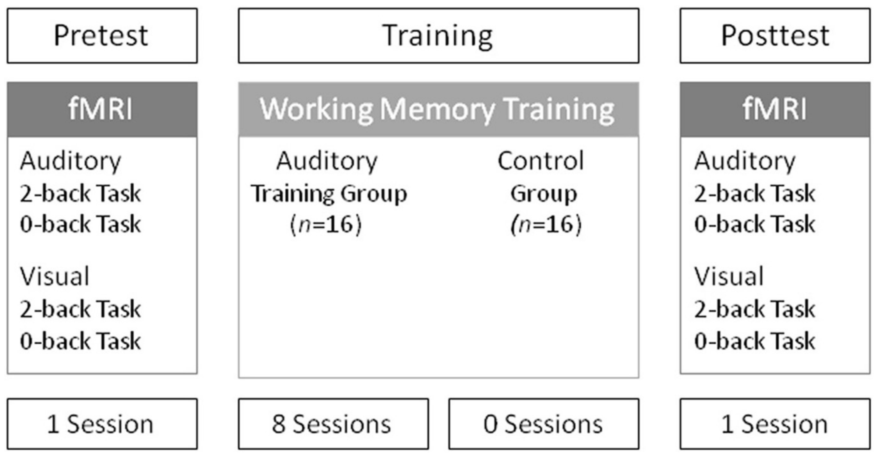

FIGURE 1 | Schematic description of the experimental design. Both groups performed the same auditory and visual 2-back and 0-back control task in the pretest and posttest fMRI session. During the training interval, the auditory training group was trained on an adaptive *n*-back task using auditory tonal sequences, whereas the control group did not receive any training.

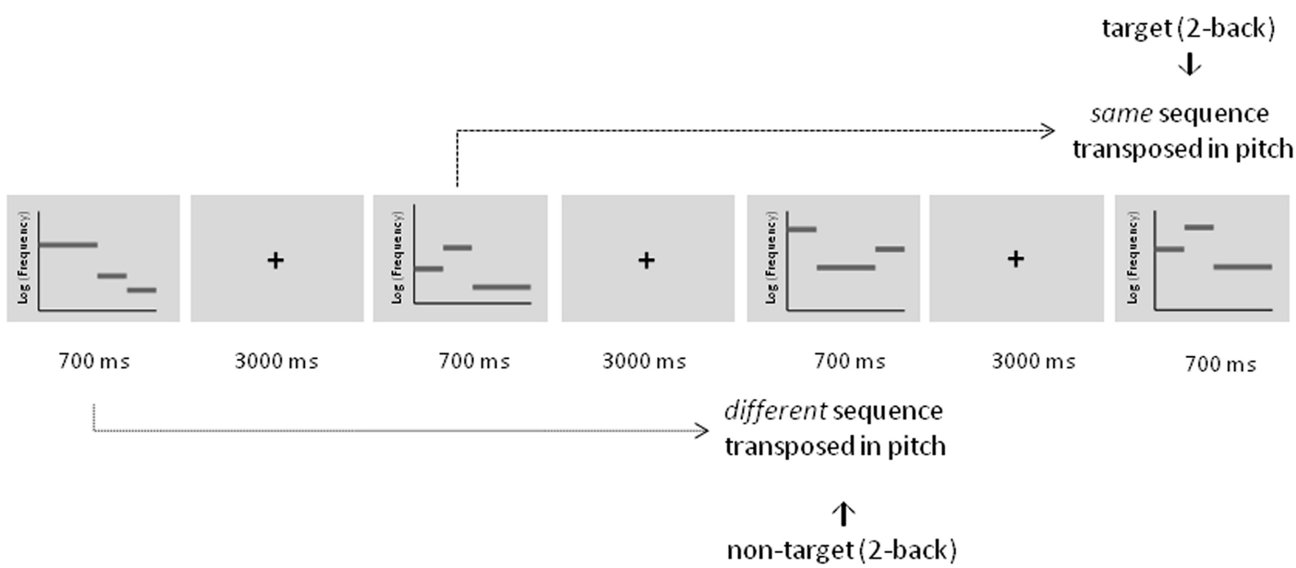

FIGURE 2 | Schematic description of the adaptive auditory *n*-back task during training illustrated for a 2-back condition. Targets were defined as tonal sequences comprising the same sequence that was transposed in pitch. Non-targets were defined as tonal sequences comprising a different sequence that was also transposed in pitch.

contained six targets with their positions determined randomly. To avoid non-targets that are most likely to distract participants' attention, non-targets immediately preceding or following a target had to be different from the target such that those trials did not function as lure trials. All other non-target stimuli were assigned randomly. Participants had to respond manually on every stimulus by pressing either the letter "M" or "C" of a standard computer keyboard. Response mappings were counterbalanced across participants and were maintained throughout training and fMRI sessions. To implement adaptivity in the task, the level of n changed from one block of $20 + n$ trails to the next according to each participant's individual performance. If the participant performed better than 78% correct, the level of n increased by 1 but decreased by 1 if accuracy was worse than 67% correct. In all other cases n remained unchanged. Each training session comprised 40 blocks and started with the n level of 1. Starting level was always $n = 1$ for motivational reasons and to assure that participants were actually able to perform the task well, before n increases. As compared to our previous study (Schneiders et al., 2011), the current auditory stimulus material as described below rendered the training task more difficult.

Rhythmic three-tone melodies were employed for the auditory working memory training. They consisted of two short pure tones lasting 175 ms (20 ms gating windows) and one long pure tone lasting 350 ms (20 ms gating windows) resulting in a total length of 700 ms. Three different tones within each melody were taken from an atonal scale and with the octave divided into seven equally spaced logarithmic steps ("tones") (see also Foxton et al., 2003, 2004). Starting pitch varied from 224.48 Hz for the most low-pitched scale and 356.30 Hz for the most high-pitched scale. In each training session a completely new set of eight stimuli was used to ensure that effects were not due to highly familiar stimulus material and to prevent verbal and semantic encoding strategies as much as possible. In each stimulus set, two stimuli featured a pitch pattern of two falls, two raises, a raise followed by a fall, or a fall followed by a raise, respectively. Stimuli with the same pitch pattern differed in the amount of frequency change between the tones (e.g., tone 1 (224.48 Hz)—tone 4 (317,19 Hz)—tone 5 (345,96 Hz) of the scale vs. tone 1 (224.48 Hz)—tone 2 (266,64 Hz)—tone 3 (290,82 Hz) of the scale). However, the absolute pitch varied between all of the stimuli within one block. Tones were not repeated within one melody. Targets were defined as melodies comprising exactly the same melody ("pitch contour") but were transposed in absolute pitch. Non-targets were pitch patterns that differed in one raise or fall compared to the original melody and were also transposed in absolute pitch.

The procedure was self-paced from one block to the next such that the amount of time to complete one training session varied between participants resulting on average 50 min per session. The training comprised eight sessions taking place within two weeks. The time lag between sessions was between one and four days.

A repeated measures analysis of variance (ANOVA) with the factors session (collapsed across two consecutive sessions) was calculated on the mean level of n as an indicator of the participants' mean performance for each session. In each training session, the first ten blocks were excluded from calculating the mean level of n because participants had to pass those levels of n, which were below their individual performance level.

PRETEST AND POSTTEST TASKS

To examine whether auditory working memory training leads to specific improvements of auditory working memory and whether it also transfers to visual working memory, an auditory and a visual 2-back task were employed as transfer tasks in the fMRI pretest and posttest (**Figure 3**).

The auditory task was different from the training task in that a constant level of $n = 2$ was employed. By this it poses less demands on maintenance and updating processes engaged by the n-back task as compared to the adaptive version of the task that requires the updating of the actual n-level every $20 + n$ trials. As during training new sets of melodies were used; stimuli were randomly assigned to the pretest and the posttest and were taken from the same pool of stimuli used in the training sessions. An auditory 0-back task using the same stimuli throughout the block was applied as a control task. In this task, a pure tone (stimulus length = 400 ms, frequency = 440 Hz, 20 ms gating windows) was overlaid on the melody. Similar to the transfer task, subjects were required to press a button upon the presentation of a target (i.e., whenever the tone was added to the melody) and another if it was not. Six targets were presented in each block. Five blocks of the auditory transfer task consisting of 22 trials alternating with five blocks of the auditory control task comprising 20 trials were completed.

After completion of the auditory transfer task an analogous visual transfer task was employed. The visual transfer task was equivalent to the task used in our previous study (Schneiders et al., 2011). Stimulus presentation was 500 ms, the inter-stimulus interval lasted 2500 ms. As in the previous study abstract black and white pattern stimuli were employed for the visual transfer and control task. In the visual control task a gray dot was added to the center of one of the stimuli. Subjects were instructed to respond upon the presentation of the target (with gray dot) by pressing one button and by pressing another button to respond to non-targets (without gray dot). Five blocks of the visual transfer task consisting of 22 trials alternating with five blocks of the visual control task comprising 20 trials were completed. During the fMRI sessions an additional run with a language task was performed which will not be reported here.

A Two-Way ANOVA with the factors Time (pretest vs. posttest) and Group (auditory working memory training vs. no training) was performed on the auditory and visual transfer task using the discrimination index *Pr [P(hits to targets)—P(false alarms to non-targets)]* (Snodgrass and Corwin, 1988) as dependent variable.

Before the pretest fMRI session, participants performed one block of each task outside the scanner to get familiar with the tasks.

fMRI ACQUISITION AND ANALYSES

Imaging data collection was performed on a 3 T scanner (Magnetom Trio, Siemens Medical Systems, Erlangen, Germany). Each participant was tested twice, in a pretest and a posttest, with separate blocks for each task (i.e., transfer task and

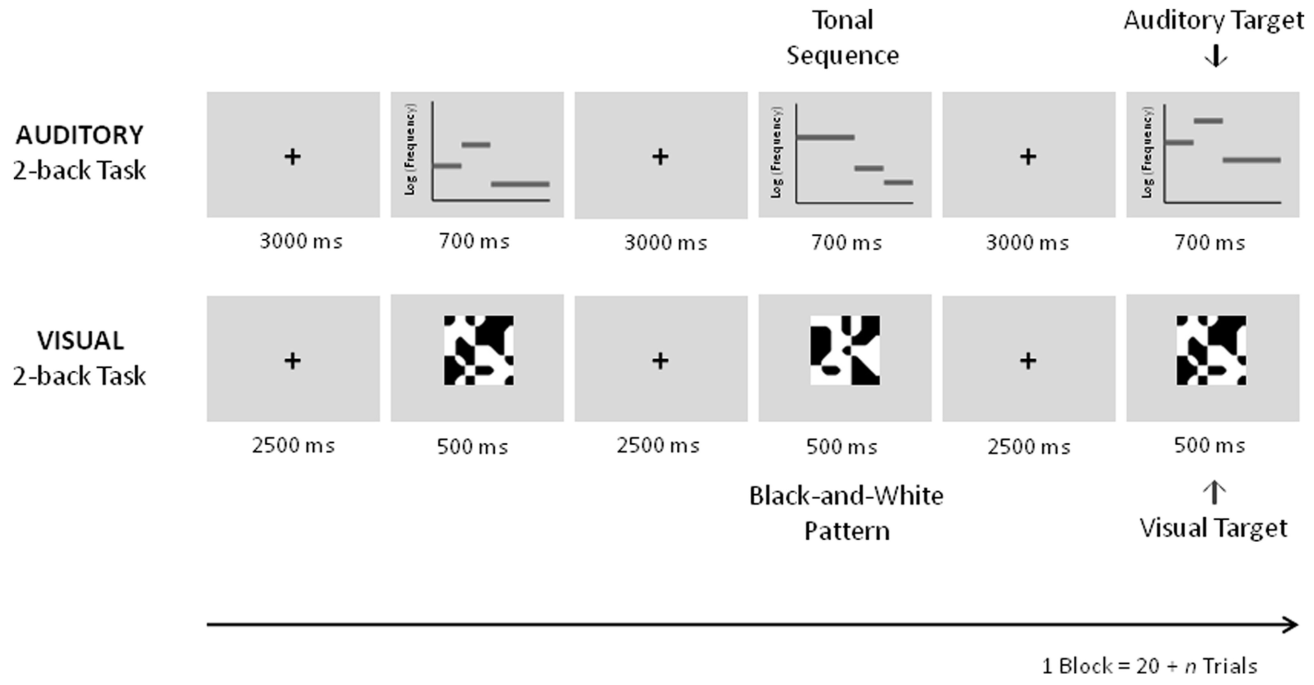

FIGURE 3 | Schematic description of the auditory and visual 2-back transfer tasks in the pre and posttest fMRI sessions. In the auditory task equivalent auditory tonal sequences as during training were used. In the visual black-and-white pattern stimuli were used.

control task) and modality (visual and auditory modality). Visual stimuli were presented through a projector onto a translucent screen. Participants viewed the stimuli through a mirror attached to the head coil. Head motions were restricted using foam padding. Responses were collected using two-button response grips. Responses were given using the left and right index finger. A T2-weighted gradient echo planar imaging sequence was used for fMRI scans (matrix = 64, field of view = 220 mm, inplane resolution = 3.5 × 3.5 mm, slice thickness/gap thickness = 3 mm/1 mm, repetition time/echo delay time /flip angle = 2300 ms/30 ms/90°). Thirty-two axial slices were acquired per volume. An intra-session high-resolution structural scan was acquired using a T1-weighted 3D magnetization prepared rapid gradient echo sequence (1 mm^3 voxel size).

The functional imaging data were analyzed using BrainVoyager QX (Brain innovation; Goebel et al., 2006). The first four volumes of each subject's functional data set were discarded to allow for T1 equilibration. For the remaining 646 volumes, standard preprocessing was performed: the images were slice time corrected (sinc interpolation), motion corrected (trilinear interpolation), and spatially smoothed using an isotopic Gaussian kernel at 5 mm full width at half maximum. The data were high-pass filtered at three cycles per run (i.e., at approximately 0.002 Hz). Functional slices were coregistered to the anatomical volume of the pretest session using position parameters and intensity-driven fine-tuning and were rescaled to a 3 × 3 × 3 mm resolution before they were transformed into Talairach coordinates (Talairach and Tournoux, 1988).

Functional time series were analyzed using random effects multi-subjects general linear model (GLM) (Friston et al., 1999). All levels of the factor Task (transfer vs. control) and the factor Time (pretest vs. posttest) were modeled as separate predictors for each subject; motion parameters were added as predictors of no interest to the design matrix of each run. Thus, the resulting GLM contained eight parameters of interest per subject: auditory transfer and auditory control, visual transfer and visual control for each of the pretest and posttest sessions. Predictor time courses were adjusted for the hemodynamic response delay by convolution with a double-gamma hemodynamic response function (Friston et al., 1998). All time points not associated with one of the eight parameters served as the implicit baseline.

To explore training-induced activation changes from pretest to posttest between the groups we performed voxel-wise whole-brain repeated measures ANOVAs *As for the analysis of the behavioral data we focused our analysis on the Time (pretest vs. posttest) by Group (training vs. no training group) interaction with the % signal changes relative to the implicit baseline for the auditory and for the visual transfer task as dependent variable. Within this analysis a main effect of Time would reflect unspecific effects of task repetition from pre-to post-test and was therefore, not evaluated.* To achieve a desirable balance between Types I and II error rates i.e., not to miss any potential activity by avoiding an unnecessarily high rate false of positives, the resulting F-maps were thresholded at a more liberal threshold of $p < 0.005$ (uncorrected) using clusters determined by the number of anatomical voxels > 135 (see Lieberman and Cunningham, 2009, for a detailed discussion). To further specify the Time by Group interaction we defined functional volumes-of-interest (VOI) on the basis of these cluster activations showing a significant Time by Group interaction. The difference of the mean activity of these clusters between pre- and posttest was then compared within each group and task.

RESULTS

BEHAVIORAL RESULTS

Performance increases during training as measured by the mean level of *n* collapsed across two consecutive training sessions are shown in **Figure 4A**. Participants improved their performance on average by 0.782 *n* (min = 0.21, max = 1.30, SEM = 0.815) from the first two training sessions to the last two training sessions. The repeated measures ANOVA revealed that the training group improved its performance as indicated by a significant main effect of Session [$F_{(3, 45)} = 54.12$, $p < 0.001$, $\eta_p^2 = 0.78$]. Moreover, a significant difference between performance at the first and second training session compared to the seventh and eighth training session substantiates these training improvements [$t_{(15)} = 9.59$, $p < 0.001$] and allows for testing the effects the training had on the posttest tasks.

The most interesting analysis according to our predictions concerns the effects of auditory training on the auditory and visual 2-back tasks from pretest to posttest compared to no training (intra-modal and across-modal transfer effects). The Three-Way ANOVA with the factors Time (pretest vs. posttest), Group (auditory training vs. no training) and Task Modality (auditory vs. visual task) revealed significant main effects of Time [$F_{(1, 30)} = 41.58$, $p < 0.001$, $\eta_p^2 = 0.58$], and Task Modality [$F_{(1, 30)} = 19.71$, $p < 0.001$, $\eta_p^2 = 0.40$]. The main effect of Group was not significant [$F_{(1, 30)} = 1.59$, $p = 0.22$, $\eta_p^2 = 0.05$]. The Two-Way interactions Time by Group [$F_{(1, 30)} = 4.26$, $p < 0.05$, $\eta_p^2 = 0.12$], Task Modality by Group [$F_{(1, 30)} = 4.61$, $p < 0.05$, $\eta_p^2 = 0.13$] and Time by Task Modality [$F_{(1, 30)} = 4.68$, $p < 0.05$, $\eta_p^2 = 0.14$] were also significant as was the Three-Way interaction [$F_{(1, 30)} = 11.63$, $p < 0.01$, $\eta_p^2 = 0.28$]. To further

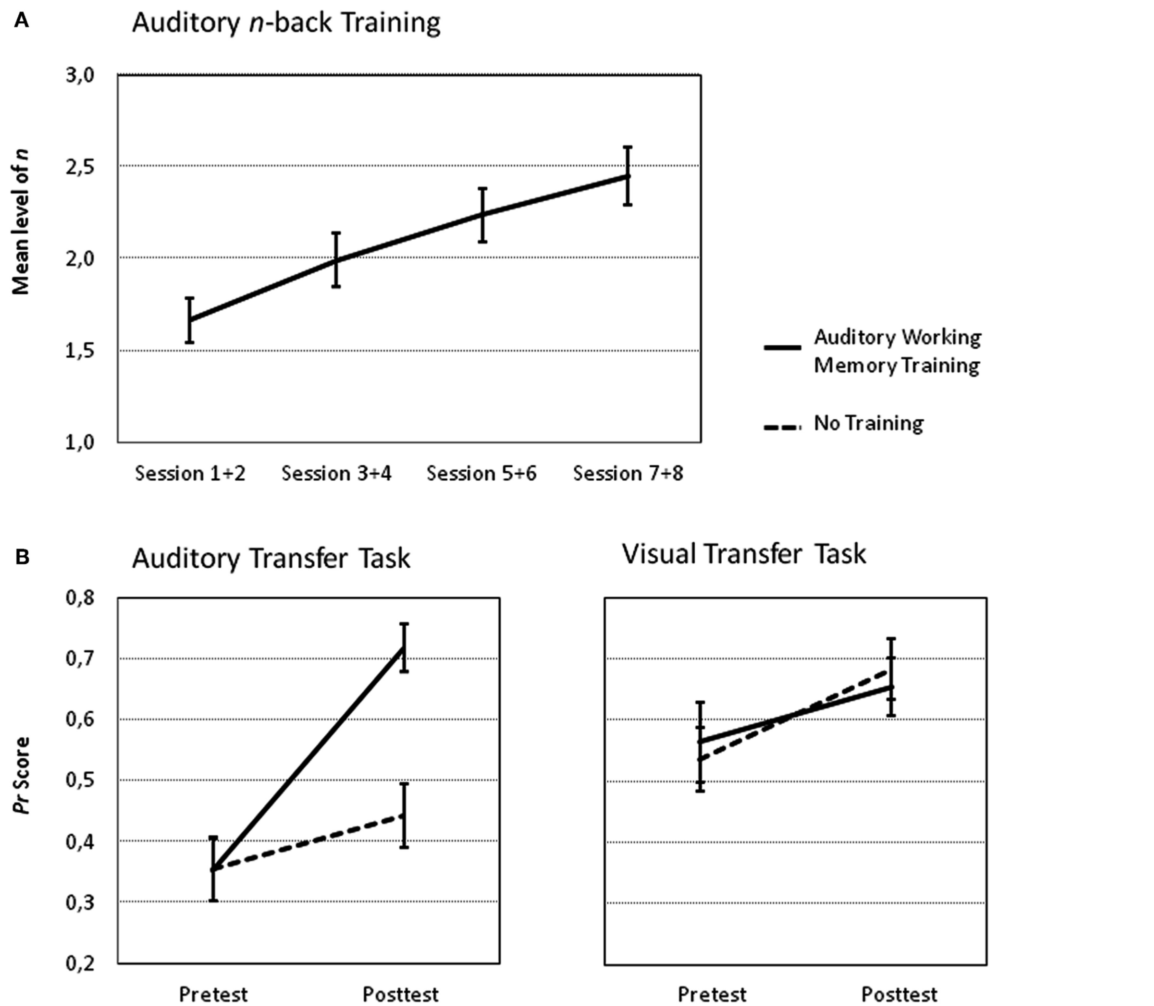

FIGURE 4 | Performance increase in the n-back task for the auditory training group. (A) The mean level of *n* as an indicator of the participants' performance for each session and corresponding standard errors of the mean are shown. **(B)** Mean Pr scores and corresponding standard errors of the mean of the auditory transfer task (left panel) and of the visual transfer task (right panel) for both groups during fMRI pretest and posttest.

explore the Three-Way interaction Two-Way ANOVAS with the factors Time (pretest vs. posttest) and Group (auditory training vs. no training) were performed separately for the two tasks. The Two-Way ANOVA on the auditory transfer task revealed a significant main effect of Time [$F_{(1, 30)} = 66.46$, $p < 0.001$, $\eta_p^2 = 0.69$] and Group [$F_{(1, 30)} = 4.65$, $p < 0.05$, $\eta_p^2 = 0.13$] and a significant Time by Group interaction [$F_{(1, 30)} = 25.23$, $p < 0.001$, $\eta_p^2 = 0.46$], reflecting group-specific improvements from pre to posttest (see **Figure 4B**). Performance did not differ between the groups in the pretest [$t_{(30)} = 0.02$, $p = 0.98$]. However, the posttest performance was significantly greater after auditory training as compared to no training [$t_{(30)} = 4.23$, $p < 0.001$]. The analogous Two-Way ANOVAs on the visual transfer task revealed a significant main effect of Time [$F_{(1, 30)} = 7.61$, $p < 0.05$, $\eta_p^2 = 0.20$] but the main effects of Group [$F_{(1, 30)} = 0.01$, $p = 0.99$, $\eta_p^2 < 0.01$] and the Time by Group interaction [$F_{(1, 30)} = 0.44$, $p = 0.51$, $\eta_p^2 = 0.01$] were not reliable.

Taken together, behavioral data shows a specific improvement of the working memory training group compared to the control group in the auditory but not in the visual transfer task.

BRAIN IMAGING RESULTS

As the main of interest of the present study was to explore changes in brain activity from pretest to posttest after auditory working memory training compared to no training the present analysis focused on voxel-wise whole-brain Time by Group interactions on the auditory transfer task. Such interactions were found in four clusters of activation, the right postcentral gyrus at BA 5, the right middle temporal gyrus at BA 21 and two clusters in the right inferior frontal gyrus, one in BA 45 and one in BA 46 (for a list of peak cluster coordinates and local maxima coordinates, see **Table 1A**). To test whether those interactions arose due to pretest activation differences between the two groups, we compared the mean activity of these clusters in the pretest auditory transfer task between the two groups. Significant pretest group differences were found in the right postcentral gyrus [$t_{(30)} = -2.01$, $p = 0.05$] and the right middle temporal gyrus [$t_{(30)} = 3.58$, $p = 0.001$]. These pretest group differences, for obvious reasons, could not be related to working memory training. Moreover, as both groups were equally naïve with respect to the 2-back task these differences are not related to the specific task demands but rather reflect some unspecific differences between groups. For this reason both clusters were excluded from further analyses and VOI analyses were restricted to the remaining two clusters in the right inferior frontal gyrus for which no pretest group differences between the two groups were found [BA 46: $t_{(30)} = 0.52$, $p = 0.61$; BA 47: $t_{(30)} = 1.54$, $p = 0.14$].

VOI analyses revealed that after working memory training activation in the auditory transfer task significantly decreased in both VOIs [BA 46: $t_{(15)} = 3.17$, $p < 0.01$, and BA 47: $t_{(15)} = 2.50$, $p < 0.05$], whereas activation significantly increased after no training in BA 46 [$t_{(15)} = -2.72$, $p < 0.05$] and BA 47 [$t_{(15)} = -2.92$, $p < 0.05$] (see **Figures 5A,B**). A next analysis tested whether the activation decreases in BA 46 and 47 were specific for the auditory 2-back task. Thus, a one-tailed paired t-test was calculated, to test whether the posttest-pretest difference was significantly larger in the auditory than in the visual transfer task. This analysis revealed significantly larger training-related changes in BA 47 [$t_{(15)} = 1.95$, $p < 0.05$] for the auditory as compared to the visual transfer task. The same analysis for BA 46 revealed a marginally significant effect [$t_{(15)} = 1.38$, $p < 0.10$]. By this, activation decreases in the two regions in the right inferior frontal gyrus after working memory training seem to be specific for the auditory transfer task.

To test for effects the training had on the visual transfer task, an analogous voxel-wise whole-brain Time by Group analysis was performed for the visual transfer task. Significant Time by Group interactions were found in three clusters in the right hemisphere, postcentral gyrus at BA 5, posterior parietal lobule at BA 40, and superior frontal gyrus at BA 6 (for a list of peak cluster coordinates and local maxima coordinates, see **Table 1B**). As marginally significant pretest differences between the groups were found in the right postcentral gyrus [$t_{(30)} = -1.75$, $p < 0.10$], this cluster was excluded from further analyses. No pretest differences between groups were obtained for BA 40 [$t_{(30)} = 0.84$, $p < 0.41$], and BA 6 [$t_{(30)} = 1.30$, $p < 0.15$]. VOI analyses revealed significant activation decreases after auditory training in the right posterior parietal lobule at BA 40 [$t_{(15)} = 4.43$, $p < 0.001$] and in the right superior frontal gyrus at BA 6 [$t_{(15)} = 3.32$, $p < 0.01$] (see **Figures 6A,B**). Activation increased significantly in the control group in BA 6: $t_{(15)} = -2.30$, $p < 0.05$, and marginally significant in BA 40, $t_{(15)} = -1.73$, $p = 0.10$. To crosscheck whether those activation changes were specific to the visual transfer task, we applied the analogous VOI analyses to the auditory transfer task although there were no significant interactions in these region in the voxel-wise whole-brain analyses. We found a similar pattern of results for the auditory task: activation decreased after auditory training in BA 40 [$t_{(15)} = 3.78$, $p < 0.01$] and in BA 6 [$t_{(15)} = 3.12$, $p = 0.01$]. In the no training control group activation did not change in BA 40 [$t_{(15)} = -1.32$, $p = 0.21$] and showed a trend towards an increase in BA 6 [$t_{(15)} = -2.04$, $p < 0.10$]. These results point to modality-general effects in the posterior parietal lobule and the prefrontal gyrus after auditory working memory training as those effects were found equivalently for the auditory and visual transfer task.

Table 1A | Brain regions activated in the voxel-wise Time by Group Interaction for the auditory transfer task.

Brain region	BA	H	*F* Value	*p* Value	Number of voxels	*x*	*y*	*z*
IFG	46	R	15.711	0.0004	183	50	31	6
IFG	47	R	13.774	0.0008	163	44	34	–3
PCG	5	R	17.993	0.0002	669	26	–41	63
MTG	21	R	13.174	0.0011	260	65	–29	–15

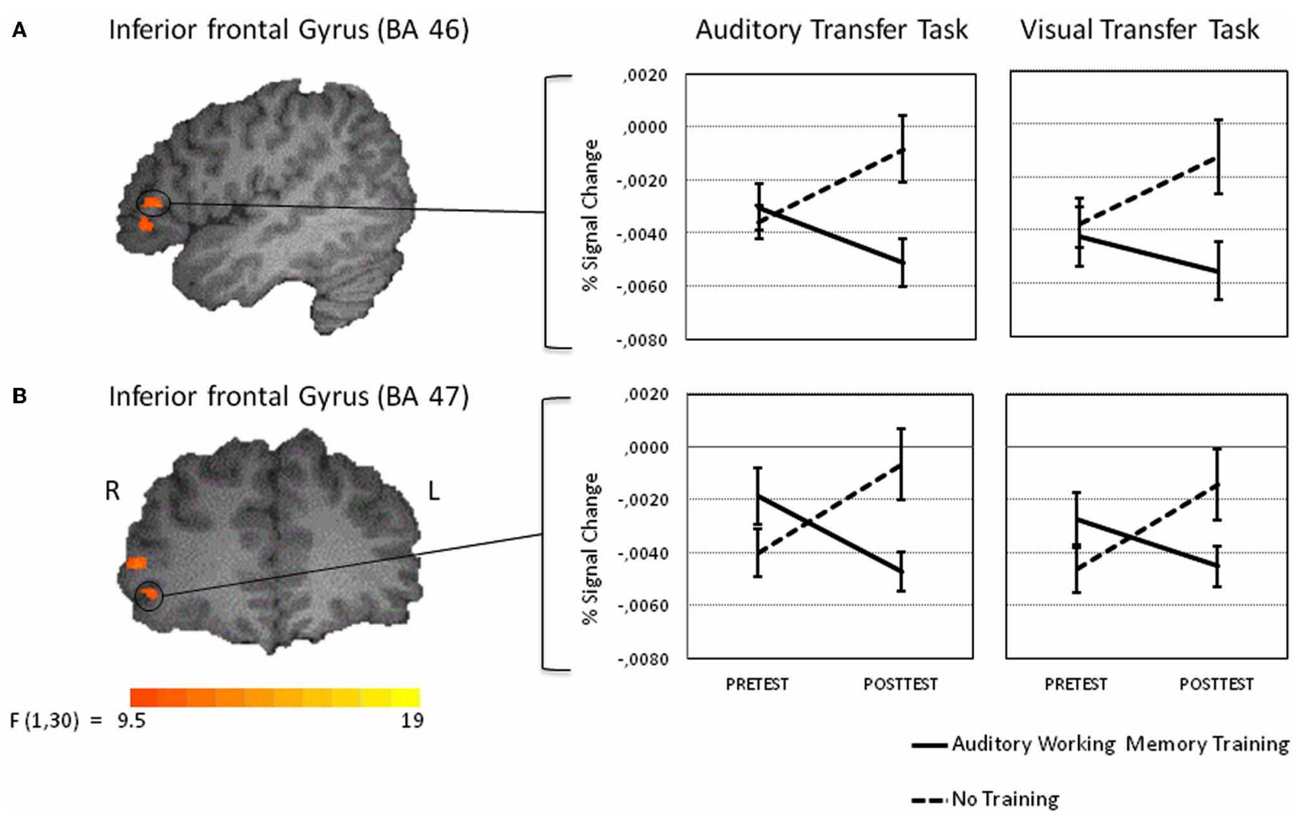

FIGURE 5 | Intra-modal training-related activation changes during the performance of the auditory transfer task (left panel). The activation changes for the visual transfer task are shown in the right panel. Percent signal change values of functional volumes of interests thresholded at $p < 0.005$ (135 voxel extend) are shown for the training and the control groups [left inferior frontal gyrus at BA 46 (**A** upper panel) and left inferior frontal gyrus at BA 47 (**B** lower panel)]. Note that the activation decrease in the training group from pre to posttest was larger in the auditory than in the visual transfer task. See results section for details.

Table 1B | Brain regions activated in the voxel-wise Time by Group Interaction for the visual transfer task.

Brain region	BA	H	*F* Value	*p* Value	Number of Voxels	*x*	*y*	*z*
IPL	40	R	18.641	0.0002	404	47	−41	42
MFG	6	R	15.156	0.0005	195	32	7	57
PCG	5	R	17.302	0.0002	226	29	−41	63

Note: H, hemisphere; R, right; IFG, inferior frontal gyrus; PCG, postcentral gyurs; MTG, middle temporal gyrus; IPL, inferior parietal lobule; MFG, middle frontal gyrus. Clusters are listed based on cluster peak coordinates and are more than 135 voxels surviving a threshold of 0.005 (uncorrected). Local maxima on which VOIs were defined (see Methods and Materials) are listed. Note that some of the clusters extend to adjacent brain areas. Coordinates correspond to those from the Talairach and Tournoux reference brain.

DISCUSSION

In this study behavioral and neural effects of auditory working memory training on an auditory and a visual working memory task were investigated. The group that performed an adaptive working memory training was compared to a control group receiving no training. Before and after training, participants were tested on an auditory and visual transfer working memory task while being scanned. Reliable training gains were found which allowed us to test for transfer effects on the pretest and posttest tasks. Performance in the auditory transfer task at posttest was higher for the training group than for the control group whereas performance in the visual transfer task did not differ from the control group after auditory working memory training.

Regarding training-related neural effects, the main finding was that auditory adaptive working memory training resulted in reduced brain activity in the right inferior frontal gyrus in the auditory task but not in the visual task. In contrast, training led to task-unspecific activation decreases in the right superior parietal lobule at BA 40 and the superior part of the right middle frontal gyrus at BA 6.

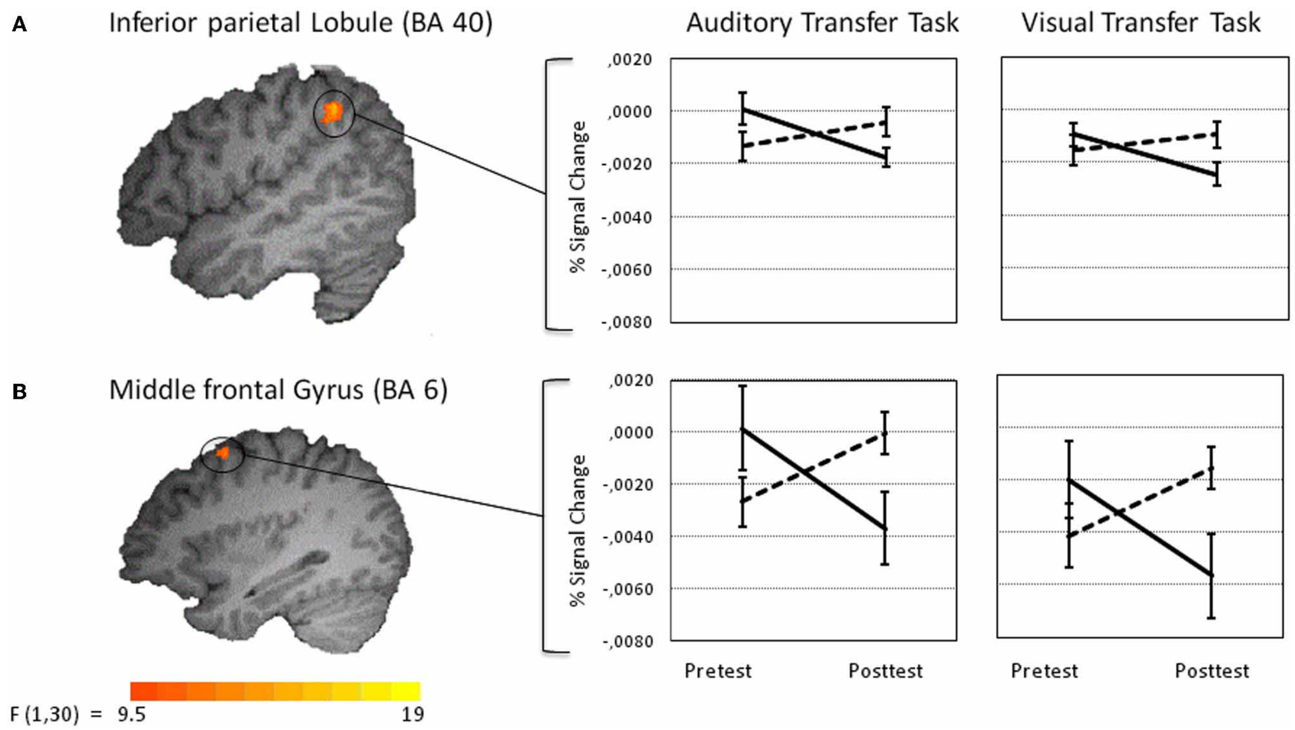

FIGURE 6 | Amodal training-related activation changes during the performance of the auditory (left panel) and visual transfer task (right panel). Percent signal change values of functional volumes of interests thresholded at $p < 0.005$ (135 voxel extend) are shown for the training (solid line) and the control group (dotted line) [right inferior parietal lobule at BA 40 (**A** upper panel) and superior part of the right middle frontal gyrus at BA 6 (**B** lower panel)].

BEHAVIORAL RESULTS

Performance improvements across the training period (training gains) were a necessary precondition for testing the effects the training had on the auditory and visual working memory tasks at posttest. This transfer effect was modality-specific insofar as performance in an equivalent visual working memory task was not affected by the training and by this indistinguishable from the no training control group. These data clearly support our hypothesis for an advantage of modality-specific training also in the auditory modality and corroborate similar modality-specific training effects for the visual modality (Schneiders et al., 2011).

Notably, those transfer effects potentially can be attributed to the specific auditory stimulus material. In the current auditory working memory training paradigm we used a set of eight global pitch sequences comprising three tones as stimulus material (adopted from Foxton et al., 2003, 2004). It is noteworthy that we found those specific training effects using stimulus material for which it was already shown that it provides a large potential for improvement in a perceptual discrimination task. A previous training study compared the trainability of discrimination global pitch patterns i.e., tonal sequences in which the pitch contour had to be compared independently of the melody's absolute pitch level, with training effects for local pitch patterns, i.e., tonal sequences in which the pitch contour differed but absolute pitch was always held constant (Foxton et al., 2004). It was shown that global pitch sequences more strongly benefited from training than local pitch patterns (Foxton et al., 2004). Presumably our modality-specific transfer effects arose because global pitch patterns are specifically distinctive and by this better memorable than other auditory material such as bird sound stimuli (Schneiders et al., 2011). In this context it needs to be acknowledged that by using three-tone sequences only four categories of raises and falls within a sequence are possible. By this participants can identify the regularity in patterns and recode them semantically and this may have additionally enhanced their memorability. Although it is still an open question whether comparable behavioral training improvements could have also be obtained with local pitch pattern sequences or other less distinct kinds of auditory information, our data clearly supports the view that auditory processes can be trained specifically.

Moreover, it needs to be mentioned that we found main effects of Time in both, the auditory and the visual transfer task. In the visual transfer task, training and control groups likewise showed improved performance at posttest indicating improvements attributable to pure repetition only. In the auditory transfer task a similar retest effect is found for the control group. These data indicate that all participants improved performance from pretest to posttest in both tasks independently of whether they received any working memory training. This shows that even a small amount of within-session practice can lead to retest effects (Garavan et al., 2000). This result is in line with many working memory training studies that likewise found main effects of Time or pure retest effects in the control group (e.g., Smith et al., 2009; Jolles et al., 2010; Owen et al., 2010; Schneiders et al., 2011) and by this makes a control group indispensable. Thus, the transfer effects on the auditory task are additive to these retest effects.

It needs to be acknowledged that there were performance differences between the auditory and the visual transfer tasks in the pretest. Thus, missing transfer effects on the visual transfer task might be explained by ceiling effects, i.e., the initially high performance level may have made further improvements impossible. However, *Pr* scores in the visual task, although higher than in the auditory task, were between 0.5 and 0.6 for the two groups and, by this, still not at ceiling. Additionally, the initial *Pr* scores in the visual transfer task were comparable to the *Pr* scores in an analogous visual transfer task in a previous training study (Schneiders et al., 2011), in which we found transfer effects after visual training. On that account it is rather unlikely that higher initial performance in the visual task of the present study prevented transfer effects on the behavioral level.

fMRI RESULTS

Intra-modal effects

Training-induced intra-modal activation decreases after working memory training were found in the auditory transfer task in two adjacent regions within the right inferior frontal gyrus (BA 46 and BA 47). These effects were accompanied by specific performance improvements. *As analogous transfer effects in the visual transfer task were substantially smaller, these effects are assumed to be rather specific for auditory information. Even though the effect size of this finding is small and the results are exploratory in nature,* they support the view that the right inferior frontal gyrus is specifically sensitive to auditory information although it is part of the common fronto-parietal working memory network which was assumed to be widely independent from input modality (Owen et al., 2005). In support of this view several lines of research indicate especially the ventral part of the inferior frontal gyrus to be selectively involved in maintaining and rehearsing auditory and phonological material (Zatorre et al., 1994; Griffiths et al., 1999; Gaab et al., 2003; Rämä and Courtney, 2005; Koelsch et al., 2009; Jerde et al., 2011).

According to the framework proposed by Kelly and Garavan (2005), the current findings can be classified as redistribution effects and suggest that auditory working memory training increased efficiency in storage, access, updating, and rehearsing of purely auditory information mediated by the inferior frontal gyrus (see also Petersen et al., 1998). Intensive and demanding updating training made these processes highly efficient, such that less neural activity is needed and better performance is achieved According to Kelly and Garavan (2005) reorganization effects are unlikely to occur after working memory training (e.g., Garavan et al., 2000; Landau et al., 2004; Olesen et al., 2004; Sayala et al., 2006; Schneiders et al., 2011), because training of working memory is less likely to result in strategic changes or enhanced automaticity during the training of the task. Instead the kind of information which needs to be maintained in working memory differs for each trial and by this always requires cognitive control processes and this is why highly similar brain regions are recruited before and after training.

Across-modal effects

Furthermore, the present study also revealed across-modal training effects at the neural level i.e., effects auditory working memory training had on the visual transfer task. As similar effects were also observed for the auditory transfer task they are task-unspecific in nature. By this, the activation decreases in the superior part of the right middle frontal gyrus at BA 6 and the right inferior parietal lobule at BA 40 can be taken to reflect alterations in amodal general control processes. Importantly, highly similar activation decreases in BA 6 and BA 40 in a visual 2-back task were found in our previous study irrespective of whether participants were trained in the visual or auditory modality before (Schneiders et al., 2011), accentuating the task- and training unspecific nature of these effects.

The superior portion of the right middle frontal gyrus is assumed to be one of the major areas for continuous updating processes in working memory (Wager and Smith, 2003), which is especially crucial for solving the *n*-back task irrespective of stimulus type. Moreover, Schubotz (2007) provides convincing support for the notion that this region is particularly recruited when predicting relevant dynamics of events, i.e., the next stimulus in serial prediction tasks. This task requires participants to monitor a sequence of abstract stimuli to work out how this sequence will evolve. Thus, participants have to update their mental representation of the sequence upon the encounter of the next stimulus. They are also asked to indicate whether the sequential order was correct until the end of presentation or whether it was violated. Importantly, to successfully solve the task participants have to predict the upcoming stimulus and to compare this predicted stimulus with the encountered one. It is reasonable to assume that successful performance in the *n*-back task entails similar predictions of the target stimulus on the basis of the prior sequence of events. For this reason, we suppose that processing requirements are functionally similar in serial prediction tasks and *n*-back tasks and by this similarly reliant on brain structures in the right middle frontal gyrus. The present task-unspecific amodal effect in this region further support the view that *n*-back working memory training leads to more efficient sequencing and prediction processes irrespective of task modality as reflected in decreased activation in this brain region in both transfer tasks.

Training-related activation decreases in the right inferior parietal lobule (BA 40) are in good agreement with findings in several working memory training studies (Hempel et al., 2004; Dahlin et al., 2008; Schneiders et al., 2011). In our previous study an equivalent decrease in the right inferior parietal lobule was found in a visual transfer task irrespective of whether the participants trained with auditory or visual materials (Schneiders et al., 2011). The intraparietal lobule is part of the fronto-parietal working memory network. This region is considered to be specifically involved in the attentional control of working memory (Jonides et al., 1998). Thereby, training-induced task-unspecific activation decreases are most likely to reflect reduced scaffolding as storage and continuous updating became more efficient and results in less demand on attentional control.

It needs to be acknowledged, that training-related activation decreases in the superior part of the right middle frontal gyrus at BA 6 and in the right inferior parietal lobule at BA 40 were accompanied by performance improvements in the auditory but not in the visual transfer task. It seems that the degree of auditory training was not yet sufficient to be also manifested in significant performance improvements in the visual transfer task. It might be that the training was not intensive enough to result in performance increases in a far transfer task that does not match the trained modality. Thus, with a longer and more intense training we would assume substantial transfer effects of auditory working memory training also to the visual transfer task, however, less pronounced than to the auditory task, due to the non-matching training and transfer modalities.

Furthermore, it was surprising that we found activation increases from pre to posttest without any training in the control group in both the auditory and the visual task. There is some evidence that within-session practice of working memory tasks can lead to alterated brain activity (see Klingberg, 2010, and Buschkuehl et al., 2012, for recent reviews). However, in these studies activation decreased independently from performance. Nevertheless some studies on working memory training found activation increases (Olesen et al., 2004; Jolles et al., 2010) or an inverted u-shaped function of activation changes (Hempel et al., 2004). But in those studies increases or the rising part of an inverted u-shaped function were only found for the training groups that trained longer than one or two sessions. Thus, the findings in our control group are not in line with those patterns of results. Alternatively, the increase of activation in the control group might be related to an increase in performance. As the control group did not practice, neural processing might not have become more efficient such that the slight increase in performance might be accompanied by more mental operation per time unit, which could have resulted in stronger activations in the respective brain areas.

Moreover, one limitation of this study is that we used a passive control group that did not receive any training. By this the groups differ in how often they came to the lab and were treated by the experimenter, which can lead to motivational differences for task performance. However, if there would be a motivational decline in the control group one would assume performance to decrease from pretest to posttest. In our data, we do not find such an effect; instead we find performance increases in the control group that are numerically comparable for the auditory and visual transfer task. Especially behavioral performance in the visual task is nearly identical to the performance of the training group. This is why we assume that factors other than working memory training are rather unlikely to account for the present data.

In conclusion, the present behavioral and functional data further strengthens the view that modality-specific training is not only possible within visual working memory (Schneiders et al., 2011) but also within the auditory modality. Specific behavioral improvements after auditory training were accompanied by specific activation decreases in the right inferior frontal gyrus. In an auditory working memory transfer task this intra-modal effect can be separated from amodal activation decreases in the right inferior parietal lobule and the superior part of the right middle frontal gyrus.

If one considers the activation changes of both our working memory training studies in conjunction, the data suggests a differentiation of the redistribution effects. Modality-specific decreases in the prefrontal cortex co-occurred with behavioral improvements: This was the case after visual training on a visual working memory task in the right middle frontal gyrus (Schneiders et al., 2011) and after auditory training on an auditory task in the right inferior frontal gyrus in the current study. In contrast, amodal activation decreases were found in more posterior regions independently of behavioral improvements irrespective of training modality in a visual transfer task (Schneiders et al., 2011) and after auditory training for a visual and an auditory transfer task in the present study.

The post training modality-specific activation decreases in the prefrontal cortex that were accompanied by improved task performance suggests that the prefrontal cortex provides most capacity for training-related efficiency. As it is known that IQ-scores negatively correlate with prefrontal cortex activation i.e., more intelligent participants show reduced activation in frontal regions compared to less intelligent ones in cognitively demanding tasks (Neubauer and Fink, 2009), it might be that prefrontal regions provide modality-specific capacities for cognitive plasticity. Last but not least these results add to our understanding of working memory systems and processes by demonstrating that additionally to a distinction between holding auditory and visual information in working memory (Baddeley, 2002, 2003; Zimmer, 2008), these systems seem to be plastic and trainable in a modality-specific way.

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REFERENCES

Baddeley, A. D. (1986). *Working Memory.* Oxford: Oxford University Press.

Baddeley, A. D. (2002). Is working memory still working? *Eur. Psychol.* 7, 85–97.

Baddeley, A. D. (2003). Working memory: looking back and looking forward. *Nat. Rev. Neurosci.* 4, 829–839.

Baddeley, A. D., Gathercole, S., and Papagno, C. (1998). The phonological loop as a language learning device. *Psychol. Rev.* 105, 158–173.

Baddeley, A. D., and Hitch, G. (1974). "The psychology of learning and motivation," in *Working Memory,* ed G. H. Bower (San Diego, CA: Academic Press), 47–89.

Baddeley, A. D., and Logie, R. H. (1999). "Working memory: the multiple-component model," in *Models of Working Memory,* eds A. Miyake and P. Shah (Cambridge, UK: Cambridge University Press), 28–61.

Buschkuehl, M., Jaeggi, S. M., and Jonides, J. (2012). Neural effects following working memory training. *Dev. Cogn. Neurosci.* 2, S167–S179.

Crottaz-Herbette, S., Anagnoson, R. T., and Menon, V. (2004). Modality effects in verbal working memory: differential prefrontal and parietal responses to auditory and visual stimuli. *Neuroimage* 21, 340–351.

Dahlin, E., Neely, A. S., Larsson, A., Bäckman, L., and Nyberg, L. (2008). Transfer of learning after updating training mediated by the striatum. *Science* 320, 1510–1512.

Erickson, K. I., Colcombe, S. J., Wadhwa, R., Bherer, L., Peterson, M. S., Scalf, P. E., Kim, J. S., Alvarado, M., and Kramer, A. F. (2007). Training-induced functional activation changes in dual-task processing: an fMRI study. *Cereb. Cortex* 17, 192–204.

Foxton, J. M., Brown, A., Chambers, S., and Griffiths, T. (2004). Training improves acoustic pattern perception. *Curr. Biol.* 14, 322–325.

Foxton, J. M., Talcott, J. B., Witton, C., Brace, H., McIntyre, F., and Griffiths, T. D. (2003). Reading skills are related to global, but not local, acoustic pattern perception. *Nat. Neurosci.* 6, 343–344.

Friston, K. J., Fletcher, P., Josephs, O., Holmes, A., Rugg, M. D., and Turner, R. (1998). Event-related fMRI: characterizing differential responses. *Neuroimage* 7, 30–40.

Friston, K. J., Holmes, A. P., Price, C. J., Büchel, C., and Worsley, K. J. (1999). Multisubject fMRI studies and conjunction analyses. *Neuroimage* 10, 385–396.

Gaab, N., Gaser, C. K., Zaehle, T., Jancke, L., and Schlaug, G. (2003). Functional anatomy of pitch memory – an fMRI study with sparse temporal sampling. *Neuroimage* 19, 1417–1426.

Garavan, H., Kelley, D., Rosen, A., Rao, S. M., and Stein, E. A. (2000). Practice-related functional activation changes in a working memory task. *Microsc. Res. Tech.* 51, 54–63.

Goebel, R., Esposito, F., and Formisano, E. (2006). Analysis of functional image analysis contest (FIAC) data with brainvoyager QX: from single-subject to cortically aligned group, general linear model analysis and self-organizing group independent component analysis. *Hum. Brain Mapp.* 27, 392–401.

Griffiths, T. D., Johnsrude, I., Dean, J. L., and Green, G. G. R. (1999). A common neural substrate for the analysis of pitch and duration pattern in segmented sounds? *Neuroreport* 10, 3825–3830.

Hempel, A., Giesel, F. L., Garcia Caraballo, N. M., Amann, M., Meyer, H., Wüstenberg, T., Essig, M., and Schröder, J. (2004). Plasticity of cortical activation related to working memory during training. *Am. J. Psychiatry* 161, 745–747.

Hossiep, R., Turck, D., and Hasella, M. (1999) *Bochumer Matrizentest—advanced version.* Göttingen, Germany: Hogrefe.

Jaeggi, S. M., Buschkuehl, M., Jonides, J., and Perrig, J. W. (2008). Improving fluid intelligence with training on working memory. *Proc. Natl. Acad. Sci. U.S.A.* 108, 6829–6833.

Jansma, J. M., Ramsey, N. F., Slagter, H. A., and Kahn, R. S. (2001). Functional anatomical correlated of controlled and automatic processing. *J. Cogn. Neurosci.* 13, 730–743.

Jerde, T. A., Childs, S. K., Handy, S. T., Nagode, J. C., and Pardo, J. V. (2011). Dissociable systems of working memory for rhythm and melody. *Neuroimage* 57, 1572–1579.

Jolles, D. D., Grol, M. J., van Buchem, M. A., Rombouts, S. A. R. B., and Crone, E. A. (2010). Practice effects in the brain: changes in cerebral activation after working memory practice depend on tasks demands. *Neuroimage* 52, 658–668.

Jonides, J. (2004). How does practice makes perfect? *Nat. Neurosci.* 7, 10–11.

Jonides, J., Schumacher, E. H., Smith, E. E., Koeppe, R. A., Awh, E., Reuter-Lorenz, P. A., Marshuetz, C., and Willis, C. R. (1998). The role of parietal cortex in verbal working memory. *J. Neurosci.* 18, 5026–5034.

Kelly, A. M., Foxe, J. J., and Garvan, H. (2006). Patterns of normal human brain plasticity after practice and their implications for neurohabilitation. *Arch. Phys. Med. Rehabil.* 87, 20–29.

Kelly, A. M. C., and Garavan, H. (2005). Human functional neuroimaging of brain changes associated with practice. *Cereb. Cortex* 15, 1089–1102.

Klingberg, T. (2010). Training and plasticity of working memory. *Trends Cogn. Sci.* 14, 317–324.

Koelsch, S., Schulze, K., Sammler, D., Fritz, T., Müller, K., and Gruber, O. (2009). Functional architecture of verbal and tonal working memory: an fMRI study. *Hum. Brain Mapp.* 3, 859–873.

Landau, S. M., Schumacher, E. H., Garavan, H., Druzgal, T. J., and D'Esposito, M. (2004). A functional MRI study of the influence of practice on component processes of working memory. *Neuroimage* 22, 211–221.

Lieberman, M. D., and Cunningham, W. A. (2009). Type I and Type II error concerns in fMRI research: re-balancing the scale. *Soc. Cogn. Affect. Neurosci.* 4, 423–428.

Lövdén, M., Bäckmann, L., Lindenberger, U., Schaefer, S., and Schmiedek, F. (2010). A theoretical framework for the study of adult cognitive plasticity. *Psychol. Bull.* 136, 659–676.

Mecklinger, A., and Opitz, B. (2003). Neglecting the parietal cortex: the role of higher-order perceptual memories for working-memory retention. *Behav. Brain Sci.* 26, 749.

Morrison, A. B., and Chein, J. M. (2011). Does working memory training work? The promise and challenges of enhancing cognition by training working memory. *Psychon. Bull. Rev.* 18, 46–60.

Neubauer, A. C., and Fink, A. (2009). Intelligence and neural efficiency: measures of brain activation versus measures of functional connectivity in the brain. *Intelligence* 37, 223–229.

Nystrom, L. E., Braver, T. S., Sabb, F. W., Delgado, M. R., Noll, D. C., and Cohen, J. D. (2000). Working memory for letters, shapes, and locations: fMRI evidence against stimulus-based regional organization in human prefrontal cortex. *Neuroimage* 11, 424–446.

Oldfield, R. C. (1971). The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia* 9, 97–113.

Olesen, P. J., Westerberg, H., and Klingberg, T. (2004). Increased prefrontal and parietal activity after training of working memory. *Nat. Neurosci.* 7, 75–79.

Owen, A. M., McMillan, K. M., Laird, A. R., and Bullmore, E. (2005). N-back working memory paradigm: a meta-analysis of normative functional neuroimaging studies. *Hum. Brain Mapp.* 25, 46–59.

Owen, A., Hampshir, A., Grahn, J. A., Stenton, R., Dajani, S., Burns, A. S., Howard, R. J., and Ballard, C. G. (2010). Putting brain training to the test. *Nature* 465, 775–779.

Petersen, S. E., van Mier, H., Fiez, J. A., and Raichle, M. E. (1998). The effects of practice on the functional anatomy of task performance. *Proc. Natl. Acad. Sci. U.S.A.* 95, 853–860.

Petrides, M., and Pandya, D. N. (2002). "Association pathways of the prefrontal cortex and functional observations," in *Principles of Frontal Lobe Function,* eds D. T. Stuss and R. T Knight (New York, NY: Oxford University Press), 31–50.

Poldrack, R. A. (2000). Comments and controversies, imaging brain plasticity: conceptual and methodological issues—a theoretical review. *Neuroimage* 12, 1–13.

Poldrack, R. A., Desmond, J. E., Glover, G. H., and Gabrieli, J. D. (1998). The neural basis of visual skill learning: an fMRI study on mirror reading. *Cereb. Cortex* 8, 1–10.

Poldrack, R. A., and Gabrieli, J. D. (2001). Characterizing the neural mechanisms of skill learning and repetition priming: evidence from mirror reading. *Brain* 124, 67–82.

Protzner, A. B., and McIntosh, A. R. (2007). The interplay of stimulus modality and response latency in neural network organization for simple working memory tasks. *J. Neurosci.* 27, 3187–3197.

Rämä, P. (2008). Domain-dependent activation during spatial and nonspatial auditory working memory. *Cogn. Process.* 9, 29–34.

Rämä, P., and Courtney, S. M. (2005). Functional topography of working memory for face or voice identity. *Neuroimage* 24, 224–234.

Rodriguez-Jimenez, R., Avila, C., Garcia-Navarro, C., Bagney, A., Aragon, A. M., Ventura-Campos, N., Martinez-Gras, I., Forn, C., Ponce, G., Rubio, G., Jimenez-Arriero, M. A., and Palomo, T. (2009). Differential dorsolateral prefrontal cortex activation during a verbal n-back task according to sensory modality. *Behav. Brain Res.* 20, 299–302.

Sayala, S., Sala, J. B., and Courtney, S. M. (2006). Increased neural efficiency with repeated performance of a working memory task is information-type dependent. *Cereb. Cortex* 16, 609–617.

Schneiders, J. A., Opitz, B., Krick, C. M., and Mecklinger, A. (2011). Separating intra-modal and across-modal training effects in visual working memory: an fMRI investigation. *Cereb. Cortex* 21, 2555–2564.

Schubotz, R. I. (2007). Prediction of external events with our motor system: towards a new framework. *Trends Cogn. Sci.* 11, 211–218.

Smith, E. E., and Jonides, J. (1997). Working memory: a view from neuroimaging. *Cogn. Psychol.* 33, 5–42.

Smith, G. E., Housen, P., Yaffe, K., Ruff, R., Kennison, R. F., Mahncke, H. W., and Zelinski, E. M. (2009). A cognitive training program based on principles of brain plasticity: results from the improvement in memory with plasticity-based adaptive cognitive training (IMPACT) study. *J. Am. Geriatr. Soc.* 57, 594–603.

Snodgrass, J. G., and Corwin, J. (1988). Pragmatics of measuring recognition memory: applications to dementia and amnesia. *J. Exp. Psychol. Gen.* 117, 34–50.

Suchan, B., Linnewerth, B., Köster, O., Daum, I., and Schmid, G. (2006). Cross-modal processing in auditory and visual working memory. *Neuroimage* 29, 853–858.

Talairach, J., and Tournoux, P. (1988). *Co-Planar Stereotaxic Atlas of the Human Brain.* New York, NY: Thieme Medical Publishers.

Wager, T. D., and Smith, E. E. (2003). Neuroimaging studies of working memory: a meta-analysis. *Cogn. Affect. Behav. Neurosci.* 3, 255–274.

Zatorre, R. J., Evans, A. C., and Meyer, E. (1994). Neural mechanisms underlying melodic perception and memory for pitch. *J. Neurosci.* 14, 1908–1919.

Zimmer, H. D. (2008). Visual and spatial working memory: from boxes to networks. *Neurosci. Biobehav. Rev.* 32, 1373–1395.

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Working-memory training in younger and older adults: training gains, transfer, and maintenance

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Working memory (WM), a key determinant of many higher-order cognitive functions, declines in old age. Current research attempts to develop process-specific WM training procedures, which may lead to general cognitive improvement. Adaptivity of the training as well as the comparison of training gains to performance changes of an active control group are key factors in evaluating the effectiveness of a specific training program. In the present study, 55 younger adults (20–30 years of age) and 45 older adults (60–70 years of age) received 5 weeks of computerized training on various spatial and verbal WM tasks. Half of the sample received adaptive training (i.e., individually adjusted task difficulty), whereas the other half-worked on the same task material but on a low task difficulty level (active controls). Performance was assessed using criterion, near-transfer, and far-transfer tasks before training, after 5 weeks of intervention, as well as after a 3-month follow-up interval. Results indicate that (a) adaptive training generally led to larger training gains than low-level practice, (b) training and transfer gains were somewhat greater for younger than for older adults in some tasks, but comparable across age groups in other tasks, (c) far-transfer was observed to a test on sustained attention and for a self-rating scale on cognitive functioning in daily life for both young and old, and (d) training gains and transfer effects were maintained across the 3-month follow-up interval across age.

Keywords: working memory, training, aging, transfer, maintenance, active control group

INTRODUCTION

Working memory (WM), the ability to maintain and manipulate information over short periods of time in the context of concurrent processing or distraction, is a key determinant of several higher-order cognitive functions, such as reasoning, fluid intelligence, problem solving, and language comprehension (Engle, 2002; Borella et al., 2010; Nettelbeck and Burns, 2010). WM functioning declines in late adulthood (Bopp and Verhaeghen, 2005; Payer et al., 2006; Borella et al., 2008) and is considered as one of the main contributing factors of various cognitive impairments in old age (Park et al., 2002). Hence, investigating the possibilities of improving WM functioning in older adults should be highly relevant to everyday cognition in late life. A large number of training studies have investigated the trainability of WM across the lifespan (for reviews, see Klingberg, 2010; Shipstead et al., 2010; Takeuchi et al., 2010; Morrison and Chein, 2011).

The benefit of a cognitive training program can be assessed by the (a) magnitude of gains in the trained tasks, (b) generalization of training effects to other non-trained tasks (transfer), and (c) stability of training and transfer effects across time (Hertzog et al., 2009). Training studies attempting at increasing WM functioning in older adults demonstrate performance gains in trained tasks and closely related non-trained WM tasks (e.g., Mahncke et al., 2006; Buschkuehl et al., 2008; Li et al., 2008; Dahlin et al., 2008a,b; Borella et al., 2010; Schmiedek et al., 2010; Richmond et al., 2011). Findings regarding far-transfer effects in old age are limited. Although generalization of WM training gains to other non-trained task domains (e.g., interference control, fluid intelligence, reasoning, reading comprehension) has been observed in younger adults (e.g., Klingberg et al., 2002; Jaeggi et al., 2008; Dahlin et al., 2008a; Chein and Morrison, 2010; but see Dahlin et al., 2008b; Owen et al., 2010), studies with older adults typically report reduced or non-existent transfer effects (e.g., Buschkuehl et al., 2008; Li et al., 2008; Dahlin et al., 2008a,b; Karbach and Kray, 2009; Borella et al., 2010; Schmiedek et al., 2010; Richmond et al., 2011; Zinke et al., 2012; but see Bherer et al., 2006; Carretti et al., 2007). Regarding the stability of training and transfer effects, there is evidence that older adults are able to maintain performance increments across months (e.g., Mahncke et al., 2006; Li et al., 2008; Dahlin et al., 2008a; Borella et al., 2010; Richmond et al., 2011; but see Buschkuehl et al., 2008).

To investigate the effects of a training program, choice of control group is critical. No-contact (passive) control groups are most commonly used. Here, participants perform pre- and post-training tests to rule out effects based on the fact that the same test is performed twice (i.e., test-retest effects), but participants are not contacted during the training phase (e.g., Li et al., 2008; Dahlin et al., 2008a; Chein and Morrison, 2010; Schmiedek et al., 2010). However, in addition to test-retest effects, the task environment (e.g., performing a specific task regularly, receiving feedback, being challenged with a new testing situation, having contact with test leaders, expectations about performance improvements due to training) might influence performance. Obviously, these influences cannot be eliminated by using a passive control group. Only few studies have used active control groups. In these studies, the controls typically perform activities unrelated to the targeted cognitive function (e.g., quizzes, questionnaires of autobiographical memory and well-being, physical activity, watching DVDs), matched on time and effort with the actual training program (e.g., Mahncke et al., 2006; Buschkuehl et al., 2008; Borella et al., 2010; Richmond et al., 2011). However, this procedure has the disadvantage that participants are engaged in quite different tasks that might affect performance differently.

In the present study, we investigated training gains, transfer effects, and 3-month maintenance effects of an intensive computerized WM training in younger and older adults. Experimental as well as control groups worked on the same training software, the only difference being that the experimental groups received adaptive training, while the control groups worked on a constant low task difficulty level. Adaptive training (e.g., individualized adjustment of task difficulty levels) is known to contribute to the efficiency of memory training and to allow individuals to make optimal use of their latent potential (Baltes et al., 1989; Klingberg et al., 2002; Brehmer et al., 2007; Hertzog et al., 2009). We used a process-specific WM training regimen (Park et al., 2007; Morrison and Chein, 2011), with abstract and new stimuli configurations presented at each trial, designed to target domain-general WM mechanisms and to minimize the formation and use of domain-specific strategies. Based on previous findings, we expected (a) younger and older adults to benefit from WM training, (b) near-transfer effects to non-trained WM tasks but also some far-transfer to tasks that share similar underlying processes (i.e., attention, reasoning), and (c) maintenance effects for younger as well as older adults across the 3-month time interval for the training gains as well as for potential transfer effects.

METHODS

PARTICIPANTS

Participants were recruited through a newspaper advertisement according to the following inclusion criteria: (a) aged between 20 and 30 years or 60–70 years, (b) healthy and no history of psychiatric or neurological disease, (c) inexperienced to computerized WM training, and (d) access to a PC with Internet connection at home.

Hundred and six adults who fulfilled the inclusion criteria were randomized to either adaptive training or low-level practice (active control) groups. Six persons withdrew from the study after baseline testing (four from the training group and two from the control group) due to technical problems, lack of time, or illness. In the final study sample, 55 younger adults (M_{age} = 26.0, 32 females) and 45 older adults (M_{age} = 63.8, 27 females) completed: (a) cognitive baseline assessment, (b) 5 weeks of intervention, and (c) cognitive post-training assessment. Only one younger adult did not attend the 3-month follow-up assessment due to moving abroad. Hence, valid results of 99 individuals were available for the 3-month follow-up assessment.

The adaptive training and control groups did not differ significantly in age, education, or gender distribution (ps > 0.80; see **Table 1** for sample descriptives). Regarding completed training days, the two intervention groups did not differ significantly, $F_{(1, 96)} = 2.8$, $p = 0.10$; however, older adults trained on average 1 day more than younger adults, 24.6 days and 23.5 days, respectively ($F_{(1, 96)} = 10.60$, $p < 0.05$, $\eta^2_p = 0.10$).

The study was approved by the local ethics committee at the Karolinska Hospital, Stockholm, Sweden. All participants were paid SEK 3000 (approximately 440 USD) for participation.

DESIGN AND PROCEDURES

This study focuses on age- and intervention-related effects in the cognitive tests assessed before and after 5 weeks of adaptive WM training/low-level practice, as well as at a 3-month follow-up. A more detailed examination of the 5 weeks of intervention is described elsewhere (Brehmer et al., 2009, 2011; Bellander et al., 2011).

Cognitive intervention

The WM training was implemented using a commercial software product (Cogmed QM), which runs on the participants' PCs at home. Individuals trained for 20–25 days (minimum 20 days) on seven verbal and non-verbal WM tasks. All tasks involved: (1) maintenance of multiple stimuli at the same time, (2) short delays during which the representation of stimuli should be held in WM, and (3) unique sequencing of stimuli order in each trail (for details of the trained tasks, see Bellander et al., 2011).

Adaptive training

In total, individuals trained on 90 WM trials per day, and needed on average 26 minutes to complete a training session. In the first session, individuals started each task at the same low difficulty level, namely remembering 2 items. Across training, task difficulty was adjusted as a function of individual performance. Specifically, task difficulty was adjusted by increasing/decreasing the number of items individuals had to remember, such that they reached approximately 60% correct per day for each task (for details about the trained tasks and the adaptive training algorithm, see Cogmed QM; www.cogmed.com, Klingberg et al., 2002). Each training session started at the task difficulty level where the participant ended in the previous session. The test leader provided feedback on the training data once a week via e-mail and controlled

Table 1 | Sample characteristics.

	Adaptive training (n = 55)		Low-level practice (n = 45)	
	Younger adults (n = 29)	Older adults (n = 26)	Younger adults (n = 26)	Older adults (n = 19)
Age	26.2 (2.8)	63.9 (3.4)	25.7 (3.5)	63.6 (3.1)
Gender distribution	18 females	15 females	14 females	12 females
Years of education	15 (2.6)	15.3 (3.4)	15.0 (2.8)	15.4 (3.5)
No. of training days	23.0 (2.0)	24.6 (1.1)	24.1 (1.5)	24.5 (1.4)

the data for potential breaks, interruptions, and unusual performance fluctuations. No problems were observed for any participant.

Low-level practice

Individuals in the active control groups worked on the same computerized WM program as the adaptive training groups. The differences between the groups were that task difficulty remained constant at the same low starting level for the controls, namely remembering two items. In addition, to adjust for time differences on task due to increased number of items per task in the adaptive training group, the control groups worked on 120 stimuli on each task and day. For motivational reasons, individuals were told to participate in speed training that may have a positive impact on cognitive functioning.

Cognitive assessment at baseline, post-training, and follow-up

Before and after the 5 weeks of intervention as well as after a 3-month time interval, all individuals were examined with the same set of eight cognitive tests to assess training-related performance gains in the criterion tasks (WM tasks) similar to the ones participants trained for 5 weeks (Span Board forward, Digit Span backward; Wechsler, 1981), near-transfer tasks (Span Board backward, Digit Span forward; Wechsler, 1981), as well as far-transfer tasks (sustained attention, PASAT, Gronwall, 1977; interference control, Stroop, Dodrill, 1978; episodic memory, RAVLT, Lezak, 1983; and non-verbal reasoning, RAVEN, Raven, 1995). In addition, participants completed a self-rating scale for cognitive functioning in daily life (CFQ; Broadbent et al., 1982) at all three measurement occasions. For more details on the tasks, see Klingberg et al. (2002) and Westerberg et al. (2007). Before baseline assessment, participants were randomly assigned to two groups receiving either adaptive training or low-level practice. Participants as well as test leaders were blind as to which experimental group individuals belonged. In addition, individuals' training accounts were locked after post-training assessment. Thus, it was not possible to practice further between post-training and 3-month follow-up assessment.

STATISTICAL ANALYSIS

Performance gains during training

This analysis was restricted to the adaptive training groups, due to the fact that the performance of the control groups was fixed at a low-level across the 5 weeks of intervention. All participants in the adaptive training groups completed at least 20 training sessions. Participants' daily performance on the seven different WM tasks was aggregated into one *t*-standardized WM performance score. Weekly WM performance scores were used for analysis (for details on the rationale and implementation of this score, see Bellander et al., 2011 and Brehmer et al., 2011). A mixed repeated-measure ANOVA was conducted with age (young, old) as between-subject factor and time (weeks 1–4) as within-subject factor to investigate performance gains during the training period and potential age differences therein.

Cognitive performance

One-Way ANOVAs were conducted separately for the eight criterion and transfer tasks and the self-rating scale of cognitive functioning to examine potential baseline differences between the age and intervention groups. To determine differences in training-related changes in the age and intervention groups, mixed repeated measure ANOVAs were conducted with age (young and old) and intervention (adaptive training and low-level practice) as between-subject factors and time (baseline, post-training, and follow-up) as within-subject factor for the eight cognitive tasks and the self-rating scale, respectively. Follow-up analyses were conducted comparing baseline to post-training and post-training to 3-month follow-up assessment. For all analyses, alpha levels were set to 0.05 and effect sizes refer to partial eta-square values.

RESULTS

PERFORMANCE GAINS DURING TRAINING

In general, younger adults showed higher performance compared to older adults ($F_{(1,\ 53)} = 29.19$, $p < 0.001$, $\eta^2_p = 0.36$). Both adaptive training groups increased their performance across the 4 weeks of training ($F_{(3,\ 51)} = 121{,}18$, $p < 0.001$, $\eta^2_p = 0.88$); however, younger adults demonstrated larger performance gains than older adults, as indicated by a reliable age × time interaction, $F_{(3,\ 51)} = 2.97$, $p = 0.04$, $\eta^2_p = 0.15$. Follow-up analysis revealed that younger adults gained more than older adults from week 1 to week 2 ($F_{(1,\ 53)} = 5.85$, $p = 0.02$, $\eta^2_p = 0.10$), although the two age groups showed comparable performance gains after week 2 (*p*s > 0.05; see **Figure 1**).

COGNITIVE BASELINE PERFORMANCE

Older adults' baseline performance was lower in all cognitive tasks and the self-rating scale compared to that of younger adults (*p*s < 0.05), the only exceptions being Digit Span forward and backward, where both age groups performed equally well (*F*s < 1). The two intervention groups did not differ in their baseline performance (*F*s < 1.3) in the self-rating scale or any of the different cognitive tasks apart from the RAVLT, where the low-level practice groups performed better than the adaptive training groups, $F_{(1,\ 96)} = 4.53$, $p = 0.04$, $\eta^2_p = 0.05$.

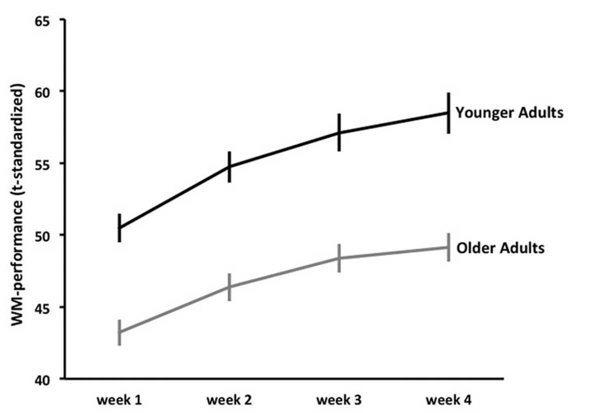

FIGURE 1 | Mean working-memory (WM) performance across 4 weeks of adaptive training. Error bars represent standard errors around the means.

INTERVENTION-RELATED PERFORMANCE CHANGES

Criterion tasks

For both criterion tasks, Span Board forward and Digit Span backward, there were performance increases across time ($F_{(2, 192)} = 39.51$, $p < 0.001$, $\eta_p^2 = 0.29$; $F_{(2, 192)} = 26.88$, $p < 0.001$, $\eta_p^2 = 0.22$, respectively). In both tasks, younger adults gained more from training than older adults ($F_{(2, 192)} = 4.24$, $p = 0.02$, $\eta_p^2 = 0.04$; $F_{(2, 192)} = 3.78$, $p = 0.02$, $\eta_p^2 = 0.04$, respectively). In addition, the adaptive training groups showed larger performance increases than the low-level practice groups ($F_{(2, 192)} = 21.85$, $p < 0.001$, $\eta_p^2 = 0.19$; $F_{(2, 192)} = 5.70$, $p < 0.001$, $\eta_p^2 = 0.06$, respectively). For Span Board forward, additional main effects for age ($F_{(1, 96)} = 54.01$, $p < 0.001$, $\eta_p^2 = 0.36$) and intervention ($F_{(1, 96)} = 20.16$, $p < 0.001$, $\eta_p^2 = 0.17$) were observed as well as an age × intervention interaction ($F_{(1, 96)} = 4.28$, $p = 0.04$, $\eta_p^2 = 0.04$). The interaction effect reflected that the difference in performance gains between the adaptive training and the low-level practice groups was larger in younger than in older adults (see **Table 2**).

Near-transfer tasks

For both near-transfer tasks, Span Board backward and Digit Span forward, performance increases across time were again observed ($F_{(2, 192)} = 50.26$, $p < 0.001$, $\eta_p^2 = 0.34$; $F_{(2, 192)} = 12.67$, $p < 0.001$, $\eta_p^2 = 0.18$, respectively). In both tasks, larger performance gains for the adaptive training than the low-level practice groups were found ($F_{(2, 192)} = 21.32$, $p < 0.001$, $\eta_p^2 = 0.18$; $F_{(2, 192)} = 5.11$, $p = 0.01$, $\eta_p^2 = 0.05$, respectively). In the Span Board backward task, main effects for age and intervention ($F_{(1, 96)} = 81.14$, $p < 0.001$, $\eta_p^2 = 0.46$; $F_{(1, 96)} = 23.10$, $p < 0.001$, $\eta_p^2 = 0.19$, respectively) were observed as well as an age × intervention interaction ($F_{(1, 96)} = 7.01$, $p = 0.01$, $\eta_p^2 = 0.07$), reflecting that the difference in performance gains between adaptive training and low-level practice groups was larger in younger than in older adults (see **Table 2**).

Far-transfer tasks

For all far cognitive transfer tasks (i.e., PASAT, Stroop, RAVLT, and RAVEN) main effects for age (*p*s < 0.01) were observed indicating higher overall performance for younger than for older adults. Apart from the RAVLT ($F < 1$), all tests showed an additional main effect of time (*p*s < 0.01), indicating general performance improvements across time for all groups. More importantly, an intervention × time interaction was observed for PASAT, $F_{(2, 192)} = 7.64$, $p = 0.001$, $\eta_p^2 = 0.07$, indicating that the adaptive training groups improved more than the low-level practice groups across the 5 weeks of intervention. No other effects reached significance (*p*s > 0.05, see **Table 2**).

Regarding the self-rating scale on cognitive functioning (CFQ), generally lower memory complaints in younger adults in comparison to older adults were observed ($F_{(1, 96)} = 9.78$, $p = 0.002$, $\eta_p^2 = 0.09$) as well as a general decrease of memory complaints across time ($F_{(2, 192)} = 9.06$, $p < 0.001$, $\eta_p^2 = 0.86$). Further, an intervention × time interaction was obtained, $F_{(2, 192)} = 3.22$, $p = 0.045$, $\eta_p^2 = 0.03$, reflecting that the adaptive training groups reduced their memory complaints more than the low-level practice groups across the 5 weeks of intervention (see **Table 2**).

Maintenance effects

Further inspection of the time-related effects revealed that in all criterion, near-transfer, as well as in two far-transfer tasks (i.e., RAVEN, PASAT), and the CFQ, the significant main effect of time was based on the difference between baseline and post-training (*p*s < 0.05), whereas post-training and 3-month follow-up performance did not differ reliably (*p*s > 0.05). Thus, the performance level reached after 5 weeks of intensive WM training was maintained across 3-months. Further, for RAVLT no performance change across time was observed; for Stroop, time on task decreases were observed after the 5 weeks of intervention as well as at the 3-month follow-up ($F_{(1, 96)} = 43.24$, $p < 0.001$, $\eta_p^2 = 0.31$; $F_{(1, 96)} = 13.06$, $p < 0.001$, $\eta_p^2 = 0.12$, respectively). For the intervention × time interaction in the criterion and near-transfer tasks, as well as for PASAT and CFQ, follow-up analyses again revealed a significant difference between baseline and post-training (*p*s < 0.05), but not between post-training and follow-up (*p*s > 0.05), indicating that the difference between adaptive training and low-level practice groups was maintained across the 3-month follow-up interval.

DISCUSSION

The present study investigated the effects of 5 weeks of intensive domain-general adaptive WM training in comparison to low-level practice in younger and older adults. Performance was assessed using criterion, near-transfer, and far-transfer tasks before training, after 5 weeks of intervention, as well as after a 3-month time interval. Younger as well as older adults gained considerably from adaptive WM training. Although younger adults showed larger training gains than older adults during the first week, both age groups gained similarly after the second week. Both younger and older adults gained more in some criterion and non-trained WM tasks (Digit Span) in comparison to controls receiving low-level practice, although we observed larger gains and transfer effects for the young in other criterion and near-transfer tasks (Span Board). Regarding far-transfer, similar performance improvements for the adaptive training as well as the active control groups were observed for tests of interference control (Stroop) and reasoning (RAVEN). These findings demonstrate general test-retest effects. More interestingly, both younger and older adults receiving adaptive training showed larger performance gains in a test measuring sustained attention (PASAT) and reported less memory complaints (CFQ) after the 5 weeks of intervention than the controls. Further, the observed training gains and transfer effects were maintained across a 3-month time interval. The same set of eight cognitive tests to assess training-related performance gains and transfer effects were used at the three assessment occasions (i.e., baseline, posttest, 3-month follow-up). Thus, potential retest influences on the observed performance changes cannot be excluded. However, this possibility does not affect the observed training and transfer effects. This is so because by including an active control group, test-retest effects were accounted for, ensuring that the additional performance changes resulted from the adaptive WM training.

Table 2 | Mean performance (SD) in criterion, near-transfer, and far-transfer tasks across age and intervention groups.

Task	Adaptive training						Low-level practice						Mixed ANOVA time × intervention interaction
	Young			Old			Young			Old			
	T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3	*p*-value
CRITERION TASKS													
Span Board Forward	5.74	7.41	7.53	5.12	5.90	6.21	5.92	6.22	6.14	5.37	5.40	5.58	< **0.01**
	(0.82)	(0.82)	(0.92)	(1.13)	(1.00)	(0.65)	(0.72)	(0.74)	(0.78)	(0.62)	(0.87)	(0.67)	< **0.01**
Digit span backward	5.07	6.76	6.86	5.21	5.94	5.69	5.29	5.67	5.92	5.21	5.5	5.79	< **0.01**
	(1.12)	(1.66)	(1.63)	(1.28)	(1.58)	(1.25)	(1.11)	(1.41)	(1.18)	(1.23)	(1.43)	(1.12)	< **0.01**
NEAR-TRANSFER TASKS													
Span Board Backward	5.64	7.14	7.22	4.59	5.69	5.9	5.56	5.83	6.17	5.08	5.26	5.24	< **0.01**
	(0.73)	(0.97)	(0.97)	(0.60)	(0.65)	(0.83)	(0.70)	(0.42)	(0.65)	(0.79)	(0.67)	(1.09)	< **0.01**
Digit Span Forward	6.35	6.98	7.14	6.29	7.02	7.02	6.58	6.79	6.98	6.37	6.45	6.32	< **0.01**
	(1.20)	(1.29)	(1.03)	(1.10)	(1.35)	(1.37)	(1.06)	(1.23)	(1.08)	(1.19)	(0.94)	(1.25)	< **0.01**
FAR-TRANSFER TASKS													
PASAT	52.52	56.41	56.34	47.77	54.38	52.85	52.62	54.77	54.62	50.63	52.00	51.68	< **0.01**
	(5.8)	(3.07)	(3.69)	(7.21)	(5.15)	(6.64)	(4.67)	(4.24)	(5.47)	(8.93)	(7.27)	(7.74)	< **0.01**
Stroop	98.31	84.14	82.86	115.54	108.04	104.19	103.35	91.23	85.08	119.79	112.05	109.84	0.78
	(16.9)	(10.99)	(12.34)	(25.17)	(20.46)	(18.56)	(16.76)	(11.57)	(8.4)	(31.86)	(25.37)	(27.44)	
RAVLT	13.07	13.76	13.72	12.15	12.12	12.23	14.04	13.85	14.08	12.63	12.68	12.53	0.36
	(1.93)	(1.38)	(1.19)	(1.91)	(1.97)	(2.14)	(0.99)	(1.41)	(1.13)	(1.67)	(2.31)	(1.84)	
RAVEN	9.38	9.93	10.07	6.58	6.5	7.12	8.96	9.81	10.00	5.84	6.84	7.21	0.28
	(2.48)	(2.20)	(2.33)	(3.14)	(3.42)	(3.28)	(2.27)	(2.10)	(2.12)	(2.71)	(3.25)	(3.43)	
CFQ	33.52	25.66	25.55	38.58	31.85	32.23	32.73	31.69	30.27	40.32	38.79	37.79	**0.04**
	(10.82)	(12.37)	(12.94)	(12.65)	(9.77)	(8.79)	(11.07)	(12.39)	(11.78)	(15.29)	(19.11)	(16.42)	

Note: T1 = Baseline, T2 = Post-training, T3 = 3-Month Follow-up.

Scores refer to raw scores (number of correct trials), except for Stroop, where time in seconds to complete the task is given.

PASAT, paced auditory serial addition task; CFQ, cognitive failures questionnaire; RAVLT, Rey auditory verbal learning test; RAVEN, Raven's standard progressive matrices set E.

Significant effects are highlighted with bold typeface.

We used a domain-general computerized WM training paradigm, which has been employed in previous studies with children, younger adults as well as persons with acquired brain lesions (Klingberg et al., 2002, 2005; Olesen et al., 2004; Westerberg et al., 2007; Holmes et al., 2009; Thorell et al., 2009; Jolles et al., 2010). These studies consistently observe near-transfer effects to non-trained WM tasks and often far-transfer effects to tests of attention, interference control, and reasoning. Our findings are in line with this previous work and other training studies in the aging domain regarding near-transfer effects to non-trained WM tasks and far-transfer to sustained attention (e.g., Mahncke et al., 2006; Mozolic et al., 2010, 2011; Richmond et al., 2011). Our expectations regarding transfer effects relied on the assumption that training and transfer tasks have to tap on similar underlying processes required for successful performance (Thorndike and Woodworth, 1901). Our domain-general WM training included processes like attention control, gating the flow of information, reducing interference while requiring maintenance of stored information, and rapid shifting between encoding and retrieval demands. Hence, the transfer of our WM intervention to the PASAT suggests that the training also improved attentional focusing.

Most often transfer effects in older adults are difficult to demonstrate and, when observed, they are reduced compared to younger adults (Buschkuehl et al., 2008; Li et al., 2008; Dahlin et al., 2008a,b; Karbach and Kray, 2009; Schmiedek et al., 2010; Richmond et al., 2011; Zinke et al., 2012). In accordance with this research, we observed larger training gains for younger than for older adults in one of the two criterion tasks (Span Board Forward) and one of the near-transfer tasks (Span Board Backward). However, younger and older adults did not differ in training and transfer effects in the two Digit Span tasks. It remains unclear why we observed age differences in the magnitude of gains for the Span Board tasks, but not for the Digit Span tasks. With regard to Digit Span, previous studies have not observed any improvements after WM training in older adults (Buschkuehl et al., 2008; Li et al., 2008; Dahlin et al., 2008b; Richmond et al., 2011). Future training studies should consider the approach suggested by Lövden et al. (2010), using established hierarchical structures of cognitive abilities instead of single tests (see also Schmiedek et al., 2010) to assess training and transfer effects. However, in our study performance gains on the PASAT as well as for the CFQ were also comparable in younger and older adults. These findings are in line with some previous studies (e.g., Bherer et al., 2006; Carretti et al., 2007) suggesting that our training paradigm is a sensitive means to detecting cognitive plasticity even in older individuals. This might reflect the adaptive algorithm used in our study, which provides a challenging task situation for the participants, the variety of verbal and non-verbal tasks used in the training program (i.e., domain-general instead of process-specific), as well as the structure and appearance of the training program.

Younger as well as older adults reported less memory complains (CFQ) after adaptive WM training in comparison to participants in the active control groups. This was the case even though participants were blind to group assignment; hence placebo/expectancy effects would be an unlikely explanation for this finding. These self-reported cognitive improvements may have important implications for everyday cognitive functioning and should be investigated further in future studies (see also Richmond et al., 2011).

The nature of our control group needs to be highlighted. To our knowledge, this is the first study in the aging domain using an active control group where individuals worked on the same task material as the experimental group, the only difference being that task difficulty was fixed at a low-level. The use of such an active control group (as opposed to no-contact controls or active controls performing different tasks) provides a conservative assessment of training effects, because the influence of various unspecific factors (e.g., stimulus-response mappings, motivation, test familiarity, performance anxiety, expectations) is attenuated (Zehnder et al., 2009; Shipstead et al., 2010). Although no direct measure of motivation was included in the present study, the uniformly high number of training sessions (i.e., 24.6 for younger adults and 23.5 for older adults) for the experimental and control groups (a minimum of only 20 sessions was required), speaks for highly engaged and committed participants in both training groups.

This conservative assessment of training and transfer gains strengthens the impact of our observed effects and suggests caution in comparing our results with other studies using passive control groups, especially in light of the fact that we observed comparable performance improvements for adaptive training groups and the controls for some of the transfer tasks (interference control, reasoning). To be able to disentangle different performance-influencing factors and to make assumptions about the value of adaptive training over low-level practice, future studies should include both active and passive (no-contact) control groups.

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REFERENCES

Baltes, P. B., Sowarka, D., and Kliegl, R. (1989). Cognitive training research on fluid intelligence in old age: what can older adults achieve by themselves? *Psychol. Aging* 4, 217–221.

Bellander, M., Brehmer, Y., Westerberg, H., Karlsson, S., Furth, D., Bergman, O., Eriksson, E., and Bäckman, L. (2011). Preliminary evidence that allelic variation in the LMX1A gene influences training-related working memory improvement. *Neuropsychologia* 49, 1938–1942.

Bherer, L., Kramer, A. F., Peterson, M. S., Colcombe, S., Erickson, K., and Becic, E. (2006). Testing the limits of cognitive plasticity in older adults: application to attentional control. *Acta Psychol. (Amst.)* 123, 261–278.

Bopp, K. L., and Verhaeghen, P. (2005). Aging and verbal memory span: a meta-analysis. *J. Gerontol. B Psychol. Sci. Soc. Sci.* 60, P223–P233.

Borella, E., Carretti, B., and De Beni, R. (2008). Working memory and inhibition across the adult life-span. *Acta Psychol. (Amst.)* 128, 33–44.

Borella, E., Carretti, B., Riboldi, F., and De Beni, R. (2010). Working memory training in older adults: evidence of transfer and maintenance effects. *Psychol. Aging* 25, 767–778.

Brehmer, Y., Li, S. C., Müller, V., Von Oertzen, T., and Lindenberger, U. (2007). Memory plasticity across the life span: uncovering children's latent potential. *Dev. Psychol.* 43, 465–478.

Brehmer, Y., Rieckmann, A., Bellander, M., Westerberg, H., Fischer, H., and Bäckman, L. (2011). Neural correlates of training-related working-memory gains in old age. *Neuroimage* 58, 1110–1120.

Brehmer, Y., Westerberg, H., Bellander, M., Furth, D., Karlsson, S., and Bäckman, L. (2009). Working memory plasticity modulated by dopamine transporter genotype. *Neurosci. Lett.* 467, 117–120.

Broadbent, D. F., Cooper, P. F., Fitzgerald, P., and Parkes, K. R. (1982). The cognitive failures questionnaire (CFQ) and its correlates. *Br. J. Clin. Psychol.* 21, 1–16.

Buschkuehl, M., Jaeggi, S. M., Hutchison, S., Perrig-Chiello, P., Dapp, C., Muller, M., Breil, F., Hoppeler, H., and Perrig, W. J. (2008). Impact of working memory training on memory performance in old-old adults. *Psychol. Aging* 23, 743–753.

Carretti, B., Borella, E., and De Beni, R. (2007). Does strategic memory training improve the working memory performance of younger and older adults? *Exp. Psychol.* 54, 311–320.

Chein, J. M., and Morrison, A. B. (2010). Expanding the mind's workspace: training and transfer effects with a complex working memory span task. *Psychon. Bull. Rev.* 17, 193–199.

Dahlin, E., Neely, A. S., Larsson, A., Bäckman, L., and Nyberg, L. (2008a). Transfer of learning after updating training mediated by the striatum. *Science* 320, 1510–1512.

Dahlin, E., Nyberg, L., Bäckman, L., and Neely, A. S. (2008b). Plasticity of executive functioning in young and older adults: immediate training gains, transfer, and long-term maintenance. *Psychol. Aging* 23, 720–730.

Dodrill, C. (1978). Neuropsychological battery for epilepsy. *Epilepsia* 19, 611–623.

Engle, R. W. (2002). Working memory capacity as executive attention. *Curr. Dir. Psychol. Sci.* 11, 19–23.

Gronwall, D. (1977). Paced auditory serial-addition task - Measure of recovery from concussion. *Percept. Mot. Skills* 44, 367–373.

Hertzog, C., Kramer, A. F., Wilson, R. S., and Lindenberger, U. (2009). Enrichment effects on adult cognitive development. *Psychol. Sci. Public Interest* 9, 1–65.

Holmes, J., Gathercole, S. E., and Dunning, D. L. (2009). Adaptive training leads to sustained enhancement of poor working memory in children. *Dev. Sci.* 12, F9–F15.

Jaeggi, S. M., Buschkuehl, M., Jonides, J., and Perrig, W. J. (2008). Improving fluid intelligence with training on working memory. *Proc. Natl. Acad. Sci. U.S.A.* 105, 6829–6833.

Jolles, D. D., Grol, M. J., Van Buchem, M. A., Rombouts, S. A., and Crone, E. A. (2010). Practice effects in the brain: changes in cerebral activation after working memory practice depend on task demands. *Neuroimage* 52, 658–668.

Karbach, J., and Kray, J. (2009). How useful is executive control training? Age differences in near and far transfer of task-switching training. *Dev. Sci.* 12, 978–990.

Klingberg, T. (2010). Training and plasticity of working memory. *Trends Cogn. Sci.* 14, 317–324.

Klingberg, T., Fernell, E., Olesen, P. J., Johnson, M., Gustafsson, P., Dahlstrom, K., Gillberg, C. G., Forssberg, H., and Westerberg, H. (2005). Computerized training of working memory in children with ADHD-a randomized, controlled trial. *J. Am. Acad. Child Adolesc. Psychiatry* 44, 177–186.

Klingberg, T., Forssberg, H., and Westerberg, H. (2002). Training of working memory in children with ADHD. *J. Clin. Exp. Neuropsychol.* 24, 781–791.

Lezak, M. D. (1983). *Neuropsychological Assessment*. New York, NY: Oxford U.P.

Li, S. C., Schmiedek, F., Huxhold, O., Rocke, C., Smith, J., and Lindenberger, U. (2008). Working memory plasticity in old age: practice gain, transfer, and maintenance. *Psychol. Aging* 23, 731–742.

Lövden, M., Bäckman, L., Lindenberger, U., Schaefer, S., and Schmiedek, F. (2010). A theoretical framework for the study of adult cognitive plasticity. *Psychol. Bull.* 136, 659–676.

Mahncke, H. W., Connor, B. B., Appelman, J., Ahsanuddin, O. N., Hardy, J. L., Wood, R. A., Joyce, N. M., Boniske, T., Atkins, S. M., and Merzenich, M. M. (2006). Memory enhancement in healthy older adults using a brain plasticity-based training program: a randomized, controlled study. *Proc. Natl. Acad. Sci. U.S.A.* 103, 12523–12528.

Morrison, A. B., and Chein, J. M. (2011). Does working memory training work? The promise and challenges of enhancing cognition by training working memory. *Psychon. Bull. Rev.* 18, 46–60.

Mozolic, J. L., Hayasaka, S., and Laurienti, P. J. (2010). A cognitive training intervention increases resting cerebral blood flow in healthy older adults. *Front. Hum. Neurosci.* 4:16. doi: 10.3389/neuro.09.016.2010

Mozolic, J. L., Long, A. B., Morgan, A. R., Rawley-Payne, M., and Laurienti, P. J. (2011). A cognitive training intervention improves modality-specific attention in a randomized controlled trial of healthy older adults. *Neurobiol. Aging* 32, 655–668.

Nettelbeck, T., and Burns, N. R. (2010). Processing speed, working memory and reasoning ability from childhood to old age. *Pers. Individ. Dif.* 48, 379–384.

Olesen, P. J., Westerberg, H., and Klingberg, T. (2004). Increased prefrontal and parietal activity after training of working memory. *Nat. Neurosci.* 7, 75–79.

Owen, A. M., Hampshire, A., Grahn, J. A., Stenton, R., Dajani, S., Burns, A. S., Howard, R. J., and Ballard, C. G. (2010). Putting brain training to the test. *Nature* 465, 775–778.

Park, D. C., Lautenschlager, G., Hedden, T., Davidson, N. S., Smith, A. D., and Smith, P. K. (2002). Models of visuospatial and verbal memory across the adult life span. *Psychol. Aging* 17, 299–320.

Park, S., Kim, M. S., and Chun, M. M. (2007). Concurrent working memory load can facilitate selective attention: evidence for specialized load. *J. Exp. Psychol. Hum. Percept. Perform.* 33, 1062–1075.

Payer, D., Marshuetz, C., Sutton, B., Hebrank, A., Welsh, R. C., and Park, D. C. (2006). Decreased neural specialization in old adults on a working memory task. *Neuroreport* 17, 487–491.

Raven, J. C. (1995). *Standard Progressive Matrices Sets A–E*. Oxford, UK: Oxford Psychologists Press Ltd.

Richmond, L. L., Morrison, A. B., Chein, J. M., and Olson, I. R. (2011). Working memory training and transfer in older adults. *Psychol. Aging* 26, 813–822.

Schmiedek, F., Lovden, M., and Lindenberger, U. (2010). Hundred days of cognitive training enhance broad cognitive abilities in adulthood: findings from the COGITO study. *Front. Aging Neurosci.* 2:27. doi: 10.3389/fnagi.2010.00027

Shipstead, Z., Redick, T. S., and Engle, R. W. (2010). Does working memory training generalize? *Psychol. Belg.* 50, 245–276.

Takeuchi, H., Taki, Y., and Kawashima, R. (2010). Effects of working memory training on cognitive functions and neural systems. *Rev. Neurosci.* 21, 427–449.

Thorell, L. B., Lindqvist, S., Nutley, S. B., Bohlin, G., and Klingberg, T. (2009). Training and transfer effects of executive functions in preschool children. *Dev. Sci.* 12, 106–113.

Thorndike, E. L., and Woodworth, R. S. (1901). The influence of improvement in one mental function upon the efficiency of other functions. *Psychol. Rev.* 8, 247–261.

Wechsler, D. (1981). *WAIS-R Manual*. New York, NY: The Psychological Corporation.

Westerberg, H., Jacobaeus, H., Hirvikoski, T., Clevberger, P., Ostensson, M. L., Bartfai, A., and Klingberg, T. (2007). Computerized working memory training after stroke - A pilot study. *Brain Inj.* 21, 21–29.

Zehnder, F., Martin, M., Altgassen, M., and Clare, L. (2009). Memory training effects in old age as markers of plasticity: a meta-analysis. *Restor. Neurol. Neurosci.* 27, 507–520.

Zinke, K., Zeintl, M., Eschen, A., Herzog, C., and Kliegel, M. (2012). Potentials and limits of plasticity induced by working memory training in old-old age. *Gerontology* 58, 79–87.

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Brain training in progress: a review of trainability in healthy seniors

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The cognitive deterioration associated with aging is accompanied by structural alterations and loss of functionality of the frontostriatal dopamine system. The question arises how such deleterious cognitive effects could be countered. Brain training, currently highly popular among young and old alike, promises that users will improve on certain neurocognitive skills, and this has indeed been confirmed in a number of studies. Based on these results, it seems reasonable to expect beneficial effects of brain training in the elderly as well. A selective review of the existing literature suggests, however, that the results are neither robust nor consistent, and that transfer and sustained effects thus far appear limited. Based on this review, we argue for a series of elements that hold potential for progress in successful types of brain training: (1) including flexibility and novelty as features of the training, (2) focusing on a number of promising, yet largely unexplored domains, such as decision-making and memory strategy training, and (3) tailoring the training adaptively to the level and progress of the individual. We also emphasize the need for covariance-based MRI methods in linking structural and functional changes in the aging brain to individual differences in neurocognitive efficiency and trainability in order to further uncover the underlying mechanisms.

Keywords: brain training, aging, plasticity, adaptiveness, individual differences, executive functions, memory

INTRODUCTION

Given the continuously growing number of elderly and their increasing longevity expectation, there is a pressing need to prolong independent functioning and to sustain quality of life by delaying the effects of cognitive decline. Human aging is typically associated with a deterioration of cognitive functioning, which is seen in multiple domains, including memory, decision-making, and cognitive control (Fisk and Sharp, 2004; Luo and Craik, 2008; Brown and Ridderinkhof, 2009). Decline is associated with shrinkage of prefrontal cortex, hippocampus, and basal ganglia (Raz et al., 2005) and alterations in their structural connectivity (O'sullivan et al., 2001; Madden et al., 2009) along with a decrease in synthesis and binding of dopamine, serotonin and acetylcholine (Wang et al., 1995, 1998; Volkow et al., 1998; Bäckman et al., 2006; Schliebs and Arendt, 2010). Together, these structural changes cause neuromodulator levels to drop, affecting important functional pathways, principally in striatal and frontostriatal areas (Bäckman et al., 2006).

A number of interventions have been suggested to slow down this decline. Offering a motivational incentive has been demonstrated to have beneficial effects on cognitive performance (Harsay et al., 2010), and individual differences in this benefit were related to several frontostriatal white matter pathways (Harsay et al., 2011). Aerobic exercise has also been shown to aid in maintaining cognitive health by reducing age-related loss and adding to volume of grey and white matter in frontal and temporal cortices (Colcombe et al., 2003, 2006). Recent DTI studies suggest a relation between exercise and increased fractional anisotropy (FA) in white matter tracts (Marks et al., 2007; Voss et al., 2010). Another set of interventions concerns mental stimulation, collectively known as brain training: activities intended to challenge cognitive abilities and induce learning. Unfortunately, the many different brain training studies employ a range of varying methods and definitions, participants are not consistently subjected to tests of transfer and long-term retention, and evidence pointing to the trainings' effectivity is inconsistent. These limitations notwithstanding, brain training is practiced by elderly on a large scale.

An important concept in the realm of cognitive training is that of transfer, the degree to which the learned skill is displayed in a different context, with near and far transfer referring to generalization of training effects to domains proximal to or more distant from the trained skill, respectively. Recent reviews of the current brain training literature on this topic conclude that training programs generally fail to display fundamental transfer, with the exception of process-based cognitive control tasks (Lustig et al., 2009; Noack et al., 2009; Papp et al., 2009). They comment on the limited methodology and arbitrary assignment of transfer tasks as either near or far, which make it difficult to draw conclusions on transferability. Furthermore, many studies do not make use of active controls, thus limiting the generalizability of results. Noack et al. (2009) also note that, given the fact that training programs mostly consist of no more than a few sessions of training, the transfer found in these cases is unlikely to be mediated by neural plasticity. In working-memory training, transfer effects are also seen to be small or nonexistent (Dahlin et al., 2009), although long-term sustained gains are reported at least for the task trained. Concerning memory, Hertzog et al. (2008) proposed that interventions should engage multiple mechanisms closely related to executive control- and other functions used by elderly on various settings in daily life.

Although a good number of articles have been written reviewing some important domains in brain training literature, we feel the need to add to the current literature by drawing attention to a number of largely unexplored perspectives, in addition to emphasizing a few promising components that may make up an effective intervention. Given the current state of brain training research in elderly, the negative overall outlook notwithstanding, a number of aspects may potentially contribute to success of future studies, which motivates our discussion of these issues in the current article. First, much attention has been paid to interventions involving cognitive control, some of which (in particular those involving cognitive flexibility) seem very promising. A systematic analysis could therefore be useful in generating an overview of the types of tasks that result in meaningful transfer and long-term retention. Second, several avenues that might well prove to be effective have yet been largely ignored in brain training research. These include decision-making and -learning, which are affected by old age and could potentially benefit from training; novelty, which prepares the neuronal system for learning and could enhance ensuing synaptic plasticity; and memory strategy training, which could transcend the memory domain and lead to far transfer. Finally, and importantly, we believe future studies can profit from a stronger emphasis on inter-individual differences in trainability. The current literature largely fails to take such individual differences and their underlying determinants into consideration. Given the massive individual differences in performance and the rate of neurocognitive decline among the elderly population, future studies thus may benefit from incorporating individual fine-tuning and adaptation into the training programs, in particular from focusing on who does and who does not benefit from a given training program, and from using neuroimaging to connect inter-individual differences in performance to perceivable differences in brain structure as well as functional connectivity and/or activation.

We will first review the current evidence on training of executive functions, arguing that persistent training of cognitive control functions can, under certain conditions, enhance performance and lead to near and far transfer. We then focus on some additional perspectives which have not yet or only modestly been implemented as an intervention, but seem to hold promise in enhancing functioning. Finally, we address the importance of recognizing the inter-individual differences in brain and behavior between elderly and its impact on cognitive training possibilities.

TRAINING EXECUTIVE FUNCTIONS

Executive functioning concerns the regulation and control of goal-directed actions. Due to the large functional dependence on prefrontal cortex and basal ganglia (Ridderinkhof et al., 2004, 2011), functions of executive control are especially prone to decline in old age (Treitz et al., 2007). It is thus reasonable to assume that training of executive functions can benefit elderly in daily life performance. This might pertain especially to tasks engaging cognitive flexibility (Buchler et al., 2008; Karbach and Kray, 2009), in other words, tasks that strengthen the general ability to adapt one's responses to the demand of the current situation and stimulate creative, novel thought. For this reason we focus strongly on executive functioning training, notably those domains that hold greatest promise in inducing flexibility. The executive functions are often divided, according to a widely adopted classification model based on latent-factor analysis by Miyake and colleagues (2000), into three separate domains of functioning: shifting, updating, and inhibition, which we will follow here.

SHIFTING

Shifting involves the flexibility to switch one's attention and one's actions between relevant tasks or subtasks, thus also dealing with interference. This is often symbolized by task switching and by multitasking. In task switching a switch is made between different aspects or properties of a stimulus, different task rules, or different effectors, frequently relying on retrieval from working memory. Multitasking (dual-tasking) requires subjects to perform several tasks concurrently, putting a strain on information processing resources.

Task switching

Studies of cognitive switching commonly report a decline in older age (Wecker et al., 2005), although there is also some evidence to the contrary (Logie et al., 2004; Della Sala et al., 2010). Age effects have been seen to diminish after extensive training on a switching task (Kramer et al., 1999), even when requiring switching between four different tasks (Buchler et al., 2008). Kray and Lindenberger (2000) differentiate between mixing and switch costs. Switch costs refer to increased latencies and error rates on switch trials compared to non-switch trials. Mixing costs are slower or more error-prone responses occurring when performing non-switch trials in the context of a switch task compared to the context of a single task. Though both types of costs can be reduced by training, mixing costs are suggested to be more compromised by aging than switch costs (Kray and Lindenberger, 2000; Kray et al., 2008), implying that aging especially affects the ability to keep multiple sets in working memory rather than making the shift itself. At the same time, mixing costs are also most sensitive to improvement (Strobach et al., 2011). Kray et al. (2008) found that when subjects verbalized their task cues before shifting to a different task, a reduction of mixing costs was seen especially in older adults compared to younger adults, whereas switch costs did not benefit from verbalizations.

Not only does training in task switching demonstrate enhancement on the task itself, recent studies also show the possibility of near and far transfer. Elderly who have grown up as bilinguals, thus constantly needing to switch between the two languages during their lifetime, are found to have an advantage in inhibitory control compared to monolingual elderly (Bialystok et al., 2004, 2006). Older adults who received training in task switching showed a reduction in mixing and switch costs on a similar switch task (Karbach and Kray, 2009; Karbach et al., 2010), but also displayed reduced interference effects on a Stroop task, and improved spatial and verbal working memory and fluid intelligence, in contrast to baseline and to elderly subjects receiving similar, non-switching related training (Karbach and Kray, 2009). In this study, demands were not only on task-set selection, but also on interference control and on goal maintenance, thus requiring use of multiple cognitive control mechanisms in one task. The fact that this intervention led to generalizable learning highlights the importance of engaging multiple mechanisms in training tasks.

Multitasking

Elderly adults generally experience greater dual-tasking costs compared to young, even when taking age-related general slowing into account (Verhaeghen et al., 2003; Bherer et al., 2005, 2008). Evidence from a recent fMRI study implies that during dual-tasking, elderly are unable to sufficiently disengage from the interruption by the second task and therefore fail to switch back to the appropriate functional network, which causes greater difficulty with dual-tasking (Clapp et al., 2011). Intervention studies show that elderly were able to benefit from dual-task training at the same rate as young. Bherer et al. (2005) trained elderly on a three-week long paradigm where visual identification and auditory discrimination were performed either concurrently or separately. Response latency was reduced in elderly to the same extent as in young adults, and accuracy improvement was even more pronounced among seniors, especially in the concurrent tasks. Near transfer was found on within-modality and cross-modality dual-task costs, and was as large (or larger) in old as in young. Assessment one month later suggested retention of the training effect. A follow-up study using two concurrent visual tasks reported similar training benefits among seniors (Bherer et al., 2008). This implies that improvement of multitasking can occur regardless of whether training consisted of same- or different-modality tasks.

Training on dual-tasking paradigms has also been suggested to transfer considerably to daily-life performance. When elderly and young subjects were trained on a driving simulation, which included a visual attention task and a visuomotor tracking task, elderly decreased their error count and response latencies to a greater extent than young adults (Hahn et al., 2010). On that same note, after computerized training on tasks combining working memory, attention, and manual control, older adults showed significant improvement in simulated driving performance (Cassavaugh and Kramer, 2009), where performance improvements on dual task effects were predictive of later driving performance improvements. Li et al. (2010) demonstrated transfer of visual discrimination multitasking to single- and double-support standing balance. Hence, multitasking interventions show generalization to activities that are directly relevant to elderly.

UPDATING

Updating, an essential aspect of working memory, refers to monitoring incoming information for its relevance and accordingly adapting the content of working memory storage, and has been linked to activation in frontopolar and dorsolateral prefrontal cortex (Salmon et al., 1996; Van Der Linden et al., 1999). Elderly performing updating tasks invest greater effort than young adults (Fiore et al., 2012). In one updating task, in which participants updated memory by remembering the smallest item on a list, four age groups (young, young-old, old, and old-old) were compared (De Beni and Palladino, 2004). Performance on this task declined more with increasing age, and older participants suffered more difficulty to suppress intrusions.

Despite age-related deficits, training of this paradigm in elderly has demonstrated opportunities for transfer. Near transfer to block-span performance was found after a 12-week training intervention (Buschkuehl et al., 2008) which included three different updating paradigms. Successful training on updating tasks was also done by Dahlin et al. (2008a,b) who trained older adults on letter-memory updating, which requires keeping a string of letters in working memory and recalling the last four letters upon ending of the task. Elderly displayed increased task performance which was maintained up to 18 months post-training, and training-related activation in striatum compared to controls.

One type of test often used to assess updating is the n-back paradigm, in which participants respond when the current stimulus matches that of n trials back. N-back tasks have been tested in elderly before, indicating the ability of elderly subjects to perform this task, even with increased working-memory demand (Verhaeghen and Basak, 2005; Van Gerven et al., 2008; Jaeggi et al., 2009). In young adults, training on this paradigm with a dual (visual and auditory) component is implied to lead to far transfer to fluid intelligence (Jaeggi et al., 2008; but see Moody (2009) for a critical evaluation).

To our knowledge, few longitudinal n-back training studies have been conducted in elderly. In one study, young and older adults were trained on a demanding spatial 2-back task (Li et al., 2008) which included blocks of regular spatial updating and trials which additionally required mental rotation. In old and young adults equally, near transfer to a more demanding spatial 3-back task and numerical 2-back and 3-back tasks was found. This performance was largely maintained 3 months after post-test. A 3-back spatial task has also been included as part of an effective multimodal training battery (Schmiedek et al., 2010). These results suggest that the older population might benefit from training on n-back tasks as well (although this claim has been contested by Engle and colleagues, see e.g., Shipstead et al., 2010). Further testing of this paradigm, including the possibility of transfer to untrained domains, seems a promising avenue for further research.

INHIBITION

Inhibition refers to the suppression of thoughts or actions, usually in favor of other thoughts or actions. Inhibition may be at play at various levels: preventing irrelevant sources of information from capturing attention, preventing irrelevant contents of information from entering working memory, pre-empting rash decisions, suppressing impulsive or undesirable actions, or overriding prepotent responses in favor of more appropriate ones. Inhibition at the levels of attention and working memory have been associated with the functionality of frontoparietal systems (Hasher and Zacks, 1988), whereas inhibition in relation to decision-making and action have been linked to the integrity of frontostriatal circuitry (Ridderinkhof et al., 2004). A variety of tasks and tests have been proposed to assess inhibitory efficiency in older adults, but many of these tasks (and associated age effects) suffer from problems with task purity, methodological confounds, and other measurement issues that are characteristic of many so-called frontal-lobe tests (Rabbitt et al., 2001). Nonetheless, there appears to be consensus that the ability to inhibit spatial responses is relatively preserved, whereas the ability to actively inhibit prepotent responses shows more robust age effects (Nieuwenhuis et al., 2000; Andres et al., 2008) in the form of reduced inhibitory control over reflexive saccades in the antisaccade task (for review, see Eenshuistra et al., 2004) and a reduced ability to interrupt actions that have already been initiated in the stop task (Williams et al., 1999).

To our knowledge, although a number of brain training studies have included inhibitory tasks in one form or other, no studies have focused specifically and systematically on whether the effects of old age on inhibitory efficiency can be remedied by training. One study reported that inhibitory skills can be trained in children (Thorell et al., 2009). That such training is feasible at least in principle in adults was demonstrated in a recent study with young adults, whose Go/NoGo proficiency improved after only a single and brief training session (Manuel et al., 2010). Evidence ubiquitously suggests age-related increases in susceptibility to interference in the Stroop task. Training studies have examined the effects of Stroop-task training in elderly, reporting performance improvement but no transfer (Dulaney and Rogers, 1994; Davidson et al., 2003). Unfortunately, the task impurity that characterizes the Stroop task (involving perceptual interference and task maintenance demands in addition to response inhibition, presumably leaving little age-related variance left to be explained by the latter) renders this task less suitable for studying the effects of age and training on inhibitory control. Using relatively more pure measures of response inhibition, age trends in inhibitory efficiency were reported in the Simon task (Maylor et al., 2011). Whether and to what extent these measures may benefit from training remains to be explored. Likewise, we are not aware of brain training studies using antisaccade tasks. Our own work has shown that antisaccade performance in the elderly may be improved considerably by motivational factors (such as reward anticipation; Harsay et al., 2010), suggesting that there may be substantial space for improvement using brain training.

SUMMARY

In sum, from the studies reviewed above it becomes evident that continuous training on cognitive control-based paradigms may not only lead to enhanced performance on the trained task, but may on occasion also extend to other, untrained, domains. This holds true in particular for tasks that capitalize in one way or other on cognitive flexibility, especially apparent in task switching paradigms (for instance, Karbach and Kray, 2009). Ideally, therefore, tasks should call on flexibility. They should engage multiple mechanisms of cognitive control at the same time, e.g., keeping a number of items in memory, shifting attention between tasks, inhibiting irrelevant stimuli while responding to another, and updating the memory trace. Subjects are thereby forced to divide their attention over a number of multimodal stimuli, creating a general state of alertness and preparedness for upcoming events that is likely to be generalized to functioning on other, nonrelated tasks.

ADDITIONAL PERSPECTIVES

A number of modalities that appear especially relevant to cognitive aging might be effectively trainable in this population, although so far there has been little investigation into these perspectives. First of all, decision-making and learning from mistakes are affected in old age, and a number of ideas to aid in dealing with these deficits are recounted below. Second, novelty can be an important key to add to training benefit in two separate ways, which will be argued here. Finally, memory strategy training has been shown to be effective in the elderly population. Though no evidence of far transfer currently exists, suggestions are given for ways to test this more thoroughly.

DECISION-MAKING

One domain that is also affected by age is decision-making and decision-learning (Brown and Ridderinkhof, 2009; Mohr et al., 2010). Older adults have more difficulty with stimulus-reward learning, taking longer to reach a criterion and displaying impaired feedback learning (Schmitt-Eliassen et al., 2007). Older individuals are generally more proficient at avoidance-learning compared to incentive-learning; they exhibit a bias to choose to avoid negative outcomes rather than gaining positive outcomes, thought to result from age-related loss of dopamine (Frank and Kong, 2008). Studies assessing learning abilities in elderly using the Iowa Gambling Task, where one needs to learn to choose cards from the most beneficial deck to optimize reward, have resulted in mixed findings. Some suggest that elderly do not sufficiently learn to pick the most profitable deck (Fein et al., 2007); others find that this impaired learning only applies to a subgroup of elderly (Denburg et al., 2006), illustrating the individual variation in this population. Increased age has also been found to be related to greater reward-related risk-taking (Cavanagh et al., 2012), in particular when learning has led to risk-avoiding behavior (Mata et al., 2011). Furthermore, it seems that elderly display an alternate activation pattern of the ventral striatum during reward anticipation and delivery. Although in elderly the ventral striatum is engaged to represent reward value, this region often fails to show activation when anticipating reward (Schott et al., 2007). Unlike in young, there is a failure to activate the insula during loss prediction (Samanez-Larkin et al., 2007), demonstrating their ability to process reward value but an inability to engage the necessary regions during anticipation.

Delay discounting refers to the preference for more immediate, smaller rewards relative to later, larger rewards. The ability to forego an immediate reward in favor of some future interest (a crucial aspect of decision-making, also in a variety of daily-life decisions) has been associated with striatal dopamine; hence, one might expect the proficiency of delay discounting to decline with age. Results are mixed and contradictory, however (e.g., Chao et al., 2009; Reimers et al., 2009; Jimura et al., 2011; Löckenhoff et al., 2011), preventing us from drawing firm conclusions at this stage.

Given these patterns of aging-related deficits in decision-making and decision-learning, and the importance for independently functioning elderly to be able to make essential decisions for themselves, one might expect decision-learning to be included in one way or other in brain training programs. We are not aware, however, of any training studies in the realm of outcome optimization. Yet, the success of such training seems feasible. For instance, anticipation of a rewarding outcome has been shown to motivate successful optimization strategies in elderly (Denburg et al., 2006; Harsay et al., 2010). Along another avenue, older decision makers appear to base their decisions on less information than younger decision makers, since this leads to only small losses in decision quality (Mata and Nunes, 2010). Thus, brain training programs might focus on training the ability to select target information economically. Moreover, aging appears to be associated specifically with deficits in rule-based decision-making processes (Mata et al., 2011) suggesting that training protocols can be targeted to learning simple and (as learning progresses) more complex decision rules in choice games, and to learning that rule-based decisions lead to favorable outcomes more often than, for instance, similarity-based decisions.

NOVELTY

Cognitive processes can be more adequately stimulated by including the important ingredient of novelty: an item, task, or activity that is unfamiliar and has not yet become subject to automatization. There are two ways in which novelty inclusion can benefit training studies and lead to reduced cognitive decline: to improve performance on existing tasks by direct inclusion of novel stimuli within training tasks, and to improve performance on new tasks by creating novel experiences and activities as the core of training. Along these lines, besides inducing novelty within tasks, an enriched environment can offer a similar effect, challenging the neuronal system to develop or protecting it from negative aging influences, as has been shown in aging animals (Winocur, 1998; Kempermann et al., 2002) as well as humans (Karp et al., 2006).

One type of intervention may contribute to protracted cognitive decline by adding features of novelty to an existing task. Stimulus repetition often leads to a decrease in neural activity as a result of more efficient neural processing (Ranganath and Rainer, 2003); by contrast, inclusion of novel stimuli is often followed by an increase in activity, and has been demonstrated to enhance synaptic plasticity, thereby posing an advantage for interventions.

Neuromodulation is believed to play an important role in the encoding of novel information into memory. Acetylcholine as well as norepinephrine have been shown to facilitate consolidation of novel stimuli by increasing the firing rate and enhancing responses to stimuli. This is also illustrated by administration of anticholinergics, which attenuates electrophysiological and hemodynamic expression of the effects of novel compared to familiar stimuli (Ranganath and Rainer, 2003).

Düzel et al. (2010) argue that novelty processing in the brain can enhance plasticity by boosting dopamine to benefit learning and memory and allow long-term consolidation to take place within the hippocampus. Dopaminergic neuromodulation occurs during and after exposure to novel stimuli, facilitating long-term potentiation and leading to consolidated synaptic plasticity. The authors suggest an integrative model of exploratory drive and neuronal plasticity to explain the connections between dopamine, novelty and plasticity, specifically in old age. According to this model, an individual is motivated to perform exploratory behavior following novelty expectation. As dopaminergic neuromodulation is subject to deterioration with increased age, elderly generally receive less reinforcement from novelty and would naturally tend less towards seeking novel stimuli in their environments, thereby creating less opportunity for plasticity and learning to take place. Although older adults benefit less from inclusion of novelty compared to younger individuals, they are still thought to benefit from a boost of dopamine to create a better learning opportunity.

Few studies have examined the role of novelty in protracting neurocognitive decline directly. One line of studies used randomized trials to investigate training abilities in elderly participants by teaching and training skills in novel activities. For instance, Bugos et al. (2007) explored individual piano instruction as a cognitive intervention in the elderly population. A group of musically naïve elderly subjects were given weekly piano and music theory lessons and were required to practice independently for 3 h each week for a period of 6 months. Compared to a control group who received no training, transfer of training was seen on Digit Symbol (a subtest of the WAIS) and the Trail Making Test, suggesting that music training led to improvement of concentration, attention, and planning abilities. Likewise, Boyke et al. (2008) studied a group of healthy elderly learning to juggle. They were given 3 months to learn and practice, and MRI scans were made directly before and after training, and 3 months after training had ended. Changes included gray-matter increases in brain areas responsible for processing of complex visual movement, and did not appear in the control group. These structural changes occurred even in individuals who were not able to perform satisfactorily at the time of testing, suggesting neuronal plasticity even among seniors who take longer to learn a new ability. A follow-up study using a small sample of young adults suggests that these structural changes might be produced by learning of the novel skill *per se*, with little further contribution from the amount of practice or the eventual quantitative increases in performance (Driemeyer et al., 2008). Unfortunately, the latter study did not make use of any control group, so that further investigation of how much practice is needed to produce structural changes remains necessary. However, so far it seems that learning novel activities can lead to improvement and transfer to other tasks, as well as to structural brain changes in old age.

Novel and challenging experiences during the lifetime are thought to also benefit cognition in old age. Neurocognitive aging processes may speed up when individuals no longer engage in work-related or social activities and hence withdraw from stimulating environments that frequently present novel stimuli or challenges (Aichberger et al., 2010; Roberts et al., 2011), possibly through weakening of neuronal connections (Cerella and Hale, 1994). Actively taking part in cognitively challenging activities is thought to function as a protective factor against cognitive decline and even decreases the risk of development of age-related diseases (Karp et al., 2006; Bialystok et al., 2007; Yaffe et al., 2009). There appears to be a strong connection between involvement in complex and challenging work during early adult life, and subsequent intellectual functioning in old age (Schooler et al., 1999). Job complexity is also believed to offer a protective factor against dementia (Potter et al., 2007). However, these studies were not able to control for confounds, leaving open the possibility that the mentioned relationship between complexity and novelty in early life and functioning in older age is bidirectional, that is, although a stimulating work environment probably affects workers' cognitive wellbeing and challenges them to broaden their intellectual horizons, individuals' already existing intellectual functioning also causes people to choose for more challenging and intellectual vocations to match their abilities. Bosma et al. (2003) analyzed the protective effects of work load on later cognitive functioning longitudinally, but controlled for a number of confounds including education and baseline intellectual abilities. When adjusting for these factors, individuals with higher workload showed a greatly decreased risk of developing later cognitive impairment.

These outcomes emphasize the promise held by the training of novel skills or the inclusion of novel stimuli in training programs. Novelty not only primes the neuronal system to prepare for learning, but the addition of continuous novel stimulation itself, be it in a standardized task or in learning a new ability, also helps build new connections and could add to individuals' motivation, providing important benefits for maintaining cognitive wellness.

MEMORY STRATEGIES

Several aspects of working memory training, such as updating, have been reviewed above. One could argue that these concentrate on training processes. This approach must be distinguished from developing new memory strategies (Kliegel and Bürki, 2012). These have a long history (Yates, 1966) and there is a considerable body of literature that demonstrates their effectiveness (Higbee, 1993). This suggests that they may also be applicable as a successful form of brain training in the elderly. Memory strategies are often taught as part of a more general memory training, which can range from learning a simple mnemonic strategy to extensive practice with a wide range of memory techniques. Rebok et al. (2007) reviewed almost 300 memory training studies with older adults using explicit criteria to judge whether the improvements due to a certain type of training could be considered evidence-based. According to the criteria, a type of training showed a beneficial effect if more than 50% of the outcome measures were both statistically significant between-group treatment effects (within-group studies were compared with baseline) and had effect sizes of at least 0.20. Evidence criteria for a certain type of memory training stipulated, furthermore, that there be at least two such studies with beneficial effects, with a minimum of 30 participants in total. Of the 218 studies considered by Rebok et al. (2007), 39 studies contribute support to 16 types of memory training which effects could be considered evidence-based. In particular, studies involving instruction in multiple mnemonic techniques led to lasting improvements (e.g., Stigsdotter and Bäckman, 1989; Hill et al., 1990; Ball et al., 2002; Dunlosky et al., 2003). Also, training specific strategies such as visual memory support (Sharps and Price-Sharps, 1996), the story mnemonic (Hill et al., 1991), and the classic loci method (Kliegl et al., 1989; Hill et al., 1991) gave significant results that qualified on the evidence-based criteria. Rebok et al. (2007, p. 54) conclude that these findings suggest "…that there are potentially several evidence-based options for older adults who wish to improve their memory and reduce memory problems."

Whereas there are clear benefits from certain types of strategy-based memory training, it is not clear at this point whether they also give rise to long-term benefits. Zelinski (2009), for example, concludes that training specific mnemonic strategies in isolation does not seem to lead to far transfer. Few studies have attempted extensive training on a variety of strategies. One example is a recent study by Craik et al. (2007) who instructed 49 older adults in a variety of mnemonic strategies (among other aspects of the training). The instruction sessions encouraged subjects to practice and find their own optimal combination, but there was no formal guidance, nor was there a computerized training that supported the optimization process. Craik et al. (2007) found no improvements on primary memory or working memory, but they did find a lasting improvement on episodic memory. A limitation of this study is that as part of the design, half the subjects had to wait three months after entering the study and initial orientation before they received the majority of the training. As the authors remark, this led a loss of motivation in the late group and hence to a loss of power in the experiment.

Craik et al. (2007) allowed subjects to control and combine their optimal strategies. Complete self-generation of strategies is thought to be a particularly effective method. In Lustig and Flegal (2008), subjects were shown individually presented words to encode and remember as well as possible. They were assigned to either a condition in which they learned to use a specific encoding strategy, or a condition in which they could choose their own strategy. Transfer to an unrelated task was found only in the strategy choice condition. This suggests that it is most beneficial to engage and train preserved albeit dormant functions in elderly by letting them initiate their own optimal strategy, in order for deep encoding processes to occur to lead to more generalizable results. Derwinger et al. (2005) also found that in older individuals, self generation of strategies is most optimal. Although subjects using learned mnemonic strategies and self-generated strategies to memorize four-digit numbers retained the same amount of information on the short-term memory tasks, long-term recollection was better in the strategy-choice condition.

We find evidence for beneficial effects of strategy-based memory training, though successful studies that yield far transfer are currently lacking. We suggest the use of a computerized approach in order to ensure that strategies are indeed being trained and to help subjects in their development and application.

SUMMARY

A number of additional modalities have been discussed that could potentially be used to add to effective training purposes, though more research is needed to confirm this. Given the aging-related deficits in decision-making and decision-learning, aspects of decision-learning might be included in training programs by focusing, for instance, on reward anticipation or rule-based decision-making. Novelty seems to be an important factor for more lasting effects of brain training, especially in elderly, and inclusion of novel stimuli or tasks could motivate elderly to invest more effort and energy into learning. In strategy-based memory training, most success is to be expected from studies that employ a variety of memory strategies, allowing considerable freedom to select optimal combinations of these, and include extensive practice.

THE INDIVIDUAL PICTURE

VARIATION WITHIN THE AGING POPULATION

One major caveat in much of the literature on brain training research concerns individual differences in the aging population. First, aging studies frequently use a comparison of retired, independent elderly of various different backgrounds to young adults, often psychology students. Besides the fact that both groups are often recruited from different sources, which impacts the validity of these studies, students and retirees are likely to differ in several other ways than age alone (e.g., length and type of education or exposure to technology), making it more difficult to attribute any observed differences directly to age-related decline and skewing the implications of age-related cognitive decline as derived from these results.

Second, and perhaps even more important, in the current literature elderly individuals are often measured as a group, without paying attention to the existing and evident differences between individuals. Elderly are likely to differ more from each other than young adults do. Genetic and environmental, traumatic and advantageous influences have a lifelong effect on each person's brain and behavior (Christensen et al., 1999; Bialystok et al., 2004; Lindenberger et al., 2008), thus exaggerating inter-individual variability as the individuals grow older. To draw conclusions on trainability of a certain task based on the mean performance of a group of elderly does little justice to individuals' strengths and weaknesses and paints a picture of the potential effects of training that is not sufficiently representative as it tends to blend all nuances in the color palette into a single shade of grey. Certain individuals might have a larger rate of cognitive decline than others, while yet others might show little decline at all. Variability in cognitive performance may result also from, for instance, illness or depression (Christensen et al., 1999). Such variation is likely to cause inconsistencies within training studies, resulting in poor conclusions about the success of certain interventions or inaccurate rejections of training paradigms that could be helpful to some, but might not work for most. Some studies that attempt to take individual variation in baseline parameters (such as working-memory capacity or general processing efficiency) into account even arrive at the conclusion that age-related differences in cognitive performance can be reduced to age-related differences in these baseline parameters (Eenshuistra et al., 2004; Della Sala et al., 2010). Current brain training research is based on the question whether a paradigm is either successful or unsuccessful; instead, we might profit more from asking for whom the training works, and how these individuals vary from the rest, in terms of behavioral and neuroimaging measures. Each person is likely to benefit from different training approaches (Yaffe et al., 2009). Some might benefit more from some tasks than from others, and some people might need more intensive training, whereas others lose motivation because training tasks do not pose enough of a challenge. Adaptive training is tailored to the needs and abilities of the individual, increasing difficulty levels as one gets better and decreasing them as more errors occur. Adding an adaptive component to the training is therefore crucial to allow people to train at their own level and keep each person challenged and motivated. Most training studies do not pay attention to this aspect, though some have (Mahncke et al., 2006; Ball et al., 2007; Smith et al., 2009). Lustig and Flegal (2008) showed that memory training performance was most effective when subjects were allowed to explore and initiate their own latent optimal strategy. It seems crucial that, during training, subjects should experience success yet stay challenged enough to increase performance. Finally, the gains associated with working-memory training were found to depend on genotypes related to the expression of dopamine in the substantia nigra (Bellander et al., 2011).

For those individuals who benefit less from brain training, alternative intervention possibilities can be explored. An important challenge, then, lies in identifying predictors of individual differences in trainability. These predictors could consist of certain neurocognitive test results, but importantly also of data on individual neural hard-wiring: neuromodulation, regional brain volume, structural and functional connectivity, or functional activation patterns. In the next section we assess in more detail the benefits that covariance-based neuroimaging techniques might provide in helping us understand individual differences in cognitive decline and trainability.

IMAGING INDIVIDUAL DIFFERENCES

Recent progress has advanced our insight in functional and structural alterations in healthy aging as related to individual performance differences (independent of baseline structural volume or age per se). For instance, BOLD (de)activation patterns can illustrate associations with reduced or retained performance. Two groups of elderly who had shown similar IQ at age 11 but whose IQ scores diverged at age 70 were compared, thus forming a group of cognitive "sustainers" and "decliners" (Waiter et al., 2008). fMRI data of the elderly group was subsequently compared to that of a young subject group. Whereas neural activation for the sustainer group did not vary from the brain regions active in young during a visual inspection task, decliners showed deactivation in a number of these areas; neural activation was found to predict individual preservation of complex reasoning skills. Similarly, in the memory domain, increased neural activation during an emotional word judgment task was observed in young adults and in a subgroup of elderly with normal performance, but not in elderly with declined memory performance (Daselaar et al., 2003). Variance in episodic recall performance has also been linked to hippocampal volume and activation change (Persson et al., 2006). Evidence that fMRI results could be applied to predict clinical cognitive decline comes from O'brien et al. (2010) demonstrating that individuals without signs of dementia at baseline but with a Clinical Dementia Rating (CDR) score of 0.5 showed a decline in hippocampal activity on an associative memory task over a period of 2 years, whereas activation patterns of those with a CDR score of 0 remained the same.

At the structural level, more complex sulcal folding was correlated with higher maintenance of cognitive processing speed

(Kochunov et al., 2010; Liu et al., 2011). Measurement of postsynaptic markers has also been related to cognitive performance in elderly. Using PET, increased caudate dopamine uptake was found to be related to higher working memory capacity while dopamine uptake in putamen was connected to increased motor speed (Landau et al., 2009). D2 receptor binding has been found to account for differences in individual cognitive performance more than age did (Bäckman et al., 2000), especially in motor functions and tasks dependent on frontal brain areas (Volkow et al., 1998). These and more recent findings suggest that individual age-related changes in prefrontal and striatal dopaminergic systems underlie performance decline (e.g., Bennett et al., 2010; Klostermann et al., 2011; Samanez-Larkin et al., 2011).

In future studies, combining some of these imaging techniques to examine the individual differences in trainability among elderly could lead to important insights about which individuals do or do not benefit from specific types of training, so that alternative interventions can be considered. For instance, striatal volume pretraining was found to account for improvement of young adults on a strategy video game (Erickson et al., 2010). Nucleus accumbens volume predicted success during early training while larger dorsal striatum volume was associated with improvement of performance throughout the training. To our knowledge, similar neuroimaging perspectives examining predictors of individual training success have currently not been investigated in the elderly brain training literature. In one study (Engvig et al., 2011), elderly subjects were scanned before and after memory training using DTI to measure changes in white matter tracts, and found an increase in FA in the training group, demonstrating the sensitivity of DTI to display differences in white matter over a period of 10 weeks. Moreover, individual memory improvement was significantly related to strength of FA change. This illustrates the possibility to show individual differences in training success in elderly, allowing future research to explore the potential of this methodology.

CONCLUSION

In pursuit of successful cognitive interventions, different training activities have been used to preserve and improve cognitive functioning in the aging population. Despite ample evidence showing that improvement is indeed possible, results are not consistently positive. We have sketched a number of ways in which future interventions could promote robust and generalized preservation of function. In order to attain long-term retention and transfer, plasticity is key. Cognitive processes can be more adequately stimulated by including the important ingredient of variability: requiring subjects to integrate cognitive functions rather than training separate mechanisms. Because cognitive domains are behaviorally and neurologically intertwined, maximal profit is reached if not just one, but multiple functions are engaged with the tasks at hand. We therefore suggest that brain training tasks be multimodal, tax cognitive flexibility, and capitalize on novelty to stimulate plasticity to the highest extent. These properties tend not to be naturally included in older adults' daily activities. Yet, this very fact points out the relevance of using these properties in this population in order to offer an optimally challenging environment. A successful brain training program should preferably include a range of different tasks to engage a multitude of functions, as well as continually offer something new in order for the neuronal system to remain challenged and to create possibilities of maximum enhancement in this population. We further argue for the importance of paying attention to individual differences in training benefit. This is possible both by incorporating adaptive elements into training, thus allowing each individual to improve at their own pace, according to their already existing abilities and in tune with their individual and momentary motivational needs. Finally, we recommend the application of innovative covariance-based neuroimaging methods to studies of brain training to investigate neural predictors of individual differences in trainability.

REFERENCES

Aichberger, M. C., Busch, M. A., Reischies, F. M., Ströhle, A., Heinz, A., and Rapp, M. A. (2010). Effect of physical inactivity on cognitive performance after 2.5 years of follow-up: longitudinal results from the survey of health, ageing, and retirement (SHARE). *GeroPsych. J. Gerontopsychol. Geriatr. Psychiatry* 23, 7.

Andres, P., Guerrini, C., Phillips, L. H., and Perfect, T. J. (2008). Differential effects of aging on executive and automatic inhibition. *Dev. Neuropsychol.* 33, 101–123.

Bäckman, L., Ginovart, N., Dixon, R. A., Wahlin, T. B., Wahlin, A., Halldin, C., and Farde, L. (2000). Age-related cognitive deficits mediated by changes in the striatal dopamine system. *Am. J. Psychiatry* 157, 635–637.

Bäckman, L., Nyberg, L., Lindenberger, U., Li, S. C., and Farde, L. (2006). The correlative triad among aging, dopamine, and cognition: current status and future prospects. *Neurosci. Biobehav. Rev.* 30, 791–807.

Ball, K., Berch, D. B., Helmers, K. F., Jobe, J. B., Leveck, M. D., Marsiske, M., Morris, J. N., Rebok, G. W., Smith, D. M., Tennstedt, S. L., Unverzagt, F. W., and Willis, S. L. (2002). Effects of cognitive training interventions with older adults - A randomized controlled trial. *JAMA* 288, 2271–2281.

Ball, K., Edwards, J. D., and Ross, L. A. (2007). The impact of speed of processing training on cognitive and everyday functions. *J. Gerontol. B Psychol. Sci. Soc. Sci.* 62, 19–31.

Bellander, M., Brehmer, Y., Westerberg, H., Karlsson, S., Fürth, D., Bergman, O., Eriksson, E., and Bäckman, L. (2011). Preliminary evidence that allelic variation in the LMX1A gene influences training-related working memory improvement. *Neuropsychologia* 49, 1938–1942.

Bennett, I. J., Madden, D. J., Vaidya, C. J., Howard, J. H. Jr., and Howard, D. V. (2010). White matter integrity correlates of implicit sequence learning in healthy aging. *Neurobiol. Aging* 32, 2317.e1–2317.e12.

Bherer, L., Kramer, A. F., Peterson, M. S., Colcombe, S., Erickson, K., and Becic, E. (2005). Training effects on dual-task performance: are there age-related differences in plasticity of attentional control? *Psychol. Aging* 20, 695–709.

Bherer, L., Kramer, A. F., Peterson, M. S., Colcombe, S., Erickson, K., and Becic, E. (2008). Transfer effects in task-set cost and dual-task cost after dual-task training in older and younger adults: further evidence for cognitive plasticity in attentional control in late adulthood. *Exp. Aging Res.* 34, 188–219.

Bialystok, E., Craik, F. I., and Freedman, M. (2007). Bilingualism as a protection against the onset of symptoms of dementia. *Neuropsychologia* 45, 459–464.

Bialystok, E., Craik, F. I., Klein, R., and Viswanathan, M. (2004). Bilingualism, aging, and cognitive control: evidence from the Simon task. *Psychol. Aging* 19, 290–303.

Bialystok, E., Craik, F. I., and Ryan, J. (2006). Executive control in a modified antisaccade task: effects of aging and bilingualism. *J. Exp. Psychol. Learn. Mem. Cogn.* 32, 1341–1354.

Bosma, H., Van Boxtel, M. P., Ponds, R. W., Houx, P. J., Burdorf, A., and Jolles, J. (2003). Mental work demands protect against cognitive impairment: MAAS prospective cohort study. *Exp. Aging Res.* 29, 33–45.

Boyke, J., Driemeyer, J., Gaser, C., Buchel, C., and May, A. (2008). Training-induced brain structure changes in the elderly. *J. Neurosci.* 28, 7031–7035.

Brown, S. B., and Ridderinkhof, K. R. (2009). Aging and the neuroeconomics of decision making: a review. *Cogn. Affect. Behav. Neurosci.* 9, 365–379.

Buchler, N. G., Hoyer, W. J., and Cerella, J. (2008). Rules and more rules: the effects of multiple tasks, extensive training, and aging on task-switching performance. *Mem. Cognit.* 36, 735–748.

Bugos, J. A., Perlstein, W. M., McCrae, C. S., Brophy, T. S., and Bedenbaugh, P. H. (2007). Individualized piano instruction enhances executive functioning and working memory in older adults. *Aging Ment. Health* 11, 464–471.

Buschkuehl, M., Jaeggi, S. M., Hutchison, S., Perrig-Chiello, P., Däpp, C., Müller, M., Breil, F., Hoppeler, H., and Perrig, W. J. (2008). Impact of working memory training on memory performance in old-old adults. *Psychol. Aging* 23, 743.

Cassavaugh, N. D., and Kramer, A. F. (2009). Transfer of computer-based training to simulated driving in older adults. *Appl. Ergon.* 40, 943–952.

Cavanagh, J. F., Neville, D., Cohen, M. X., Van de Vijver, I., Harsay, H., Watson, P., Buitenweg, J. I., and Ridderinkhof, K. R. (2012). Individual differences in risky decision-making among seniors reflect increased reward sensitivity. *Front. Neurosci.* 6:111. doi: 10.3389/fnins.2012.00111

Cerella, J., and Hale, S. (1994). The rise and fall in information-processing rates over the life span. *Acta Psychol. (Amst.)* 86, 109–197.

Chao, L. W., Szrek, H., Pereira, N. S., and Pauly, M. V. (2009). Time preference and its relationship with age, health, and survival probability. *Judgm. Decis. Mak.* 4, 1.

Christensen, H., Mackinnon, A. J., Korten, A. E., Jorm, A. F., Henderson, A. S., Jacomb, P., and Rodgers, B. (1999). An analysis of diversity in the cognitive performance of elderly community dwellers: individual differences in change scores as a function of age. *Psychol. Aging* 14, 365–379.

Clapp, W. C., Rubens, M. T., Sabharwal, J., and Gazzaley, A. (2011). Deficit in switching between functional brain networks underlies the impact of multitasking on working memory in older adults. *Proc. Natl. Acad. Sci. U.S.A.* 108, 7212–7217.

Colcombe, S. J., Erickson, K. I., Raz, N., Webb, A. G., Cohen, N. J., McAuley, E., and Kramer, A. F. (2003). Aerobic fitness reduces brain tissue loss in aging humans. *J. Gerontol. A Biol. Sci. Med. Sci.* 58, 176–180.

Colcombe, S. J., Erickson, K. I., Scalf, P. E., Kim, J. S., Prakash, R., McAuley, E., Elavsky, S., Marquez, D. X., Hu, L., and Kramer, A. F. (2006). Aerobic exercise training increases brain volume in aging humans. *J. Gerontol. A Biol. Sci. Med. Sci.* 61, 1166–1170.

Craik, F. I. M., Winocur, G., Palmer, H., Binns, M. A., Edwards, M., Bridges, K., Glazer, P., Chavannes, R., and Stuss, D. T. (2007). Cognitive rehabilitation in the elderly: effects on memory. *J. Int. Neuropsychol. Soc.* 13, 132–142.

Dahlin, E., Bäckman, L., Neely, A. S., and Nyberg, L. (2009). Training of the executive component of working memory: subcortical areas mediate transfer effects. *Restor. Neurol. Neurosci.* 27, 405–419.

Dahlin, E., Neely, A. S., Larsson, A., Bäckman, L., and Nyberg, L. (2008a). Transfer of learning after updating training mediated by the striatum. *Science* 320, 1510–1512.

Dahlin, E., Nyberg, L., Bäckman, L., and Neely, A. S. (2008b). Plasticity of executive functioning in young and older adults: immediate training gains, transfer, and long-term maintenance. *Psychol. Aging* 23, 720–730.

Daselaar, S. M., Veltman, D. J., Rombouts, S. A., Raaijmakers, J. G., and Jonker, C. (2003). Neuroanatomical correlates of episodic encoding and retrieval in young and elderly subjects. *Brain* 126, 43–56.

Davidson, D. J., Zacks, R. T., and Williams, C. C. (2003). Stroop interference, practice, and aging. *Neuropsychol. Dev. Cogn. B Aging Neuropsychol. Cogn.*10, 85–98.

De Beni, R., and Palladino, P. (2004). Decline in working memory updating through ageing: intrusion error analyses. *Memory* 12, 75–89.

Della Sala, S., Foley, J. A., Beschin, N., Allerhand, M., and Logie, R. H. (2010). Assessing dual-task performance using a paper-and-pencil test: normative data. *Arch. Clin. Neuropsychol.* 25, 410–419.

Denburg, N. L., Recknor, E. C., Bechara, A., and Tranel, D. (2006). Psychophysiological anticipation of positive outcomes promotes advantageous decision-making in normal older persons. *Int. J. Psychophysiol.* 61, 19–25.

Derwinger, A., Stigsdotter Neely, A., Macdonald, S., and Bäckman, L. (2005). Forgetting numbers in old age: strategy and learning speed matter. *Gerontology* 51, 277–284.

Driemeyer, J., Boyke, J., Gaser, C., Buchel, C., and May, A. (2008). Changes in gray matter induced by learning–revisited. *PLoS ONE* 3:e2669. doi: 10.1371/journal.pone.0002669

Dulaney, C. L., and Rogers, W. A. (1994). Mechanisms underlying reduction in Stroop interference with practice for young and old adults. *J. Exp. Psychol. Lear. Mem. Cogn.* 20, 470.

Dunlosky, J., Kubat-Silman, A. K., and Hertzog, C. (2003). Training monitoring skills improves older adults' self-paced associative learning. *Psychol. Aging* 18, 340–345.

Düzel, E., Bunzeck, N., Guitart-Masip, M., and Düzel, S. (2010). NOvelty-related motivation of anticipation and exploration by dopamine (NOMAD): implications for healthy aging. *Neurosci. Biobehav. Rev.* 34, 660–669.

Eenshuistra, R. M., Ridderinkhof, K. R., and Molen, M. W. (2004). Age-related changes in antisaccade task performance: inhibitory control or working-memory engagement? *Brain Cogn.* 56, 177–188.

Engvig, A., Fjell, A. M., Westlye, L. T., Moberget, T., Sundseth, O., Larsen, V. A., and Walhovd, K. B. (2011). Memory training impacts short-term changes in aging white matter: a longitudinal diffusion tensor imaging study. *Hum. Brain Mapp.* doi: 10.1002/hbm.21370. [Epub ahead of print].

Erickson, K. I., Boot, W. R., Basak, C., Neider, M. B., Prakash, R. S., Voss, M. W., Graybiel, A. M., Simons, D. J., Fabiani, M., Gratton, G., and Kramer, A. F. (2010). Striatal volume predicts level of video game skill acquisition. *Cereb. Cortex* 20, 2522–2530.

Fein, G., McGillivray, S., Finn, P., Band, G., Ridderinkhof, K., Segalowitz, S., Bechara, A., Damasio, A., Damasio, H., and Anderson, S. (2007). Older adults make less advantageous decisions than younger adults: cognitive and psychological correlates. *J. Int. Neuropsychol. Soc.* 13, 480–489.

Fiore, F., Borella, E., Mammarella, I. C., and De Beni, R. (2012). Age differences in verbal and visuo-spatial working memory updating: evidence from analysis of serial position curves. *Memory* 20, 14–27.

Fisk, J. E., and Sharp, C. A. (2004). Age-related impairment in executive functioning: updating, inhibition, shifting, and access. *J. Clin. Exp. Neuropsychol.* 26, 874–890.

Frank, M. J., and Kong, L. (2008). Learning to avoid in older age. *Psychol. Aging* 23, 392–398.

Hahn, M., Falkenstein, M., and Wild-Wall, N. (2010). Age-related performance differences in compensatory tracking under a dual task condition. *Occup. Ergon.* 9, 75–86.

Harsay, H. A., Buitenweg, J. I. V., Wijnen, J. G., Guerreiro, M. J. S., and Ridderinkhof, K. R. (2010). Remedial effects of motivational incentive on declining cognitive control in healthy aging and Parkinson's disease. *Front. Aging Neurosci.* 2:144. doi: 10.3389/fnagi.2010.00144

Harsay, H. A., Cohen, M. X., Reneman, L., and Ridderinkhof, K. R. (2011). How the aging brain translates motivational incentive into action: the role of individual differences in striato-cortical white matter pathways. *Dev. Cogn. Neurosci.* 1, 530–539.

Hasher, L., and Zacks, R. T. (1988). Working memory, comprehension, and aging: A review and a new view. *Psychol. Learn. Motiv.* 22, 193–225.

Hertzog, C., Kramer, A. F., Wilson, R. S., and Lindenberger, U. (2008). Enrichment effects on adult cognitive development. *Psychol. Sci. Public Interest* 9, 1.

Higbee, K. L. (1993). *Your Memory: How it Works and How to Improve it.* New York, NY: Paragon house.

Hill, R. D., Allen, C., and McWhorter, P. (1991). Stores as a mnemonic aid for older learners. *Psychol. Aging* 6, 484–486.

Hill, R. D., Storandt, M., and Simeone, C. (1990). The effects of memory skills training and incentives on free recall in older learners. *J. Gerontol.* 45, 227–232.

Jaeggi, S. M., Buschkuehl, M., Jonides, J., and Perrig, W. J. (2008). Improving fluid intelligence with training on working memory. *Proc. Natl. Acad. Sci. U.S.A.* 105, 6829.

Jaeggi, S. M., Schmid, C., Buschkuehl, M., and Perrig, W. J. (2009). Differential age effects in load-dependent memory processing. *Neuropsychol. Dev. Cogn. B Aging Neuropsychol. Cogn.* 16, 80–102.

Jimura, K., Myerson, J., Hilgard, J., Keighley, J., Braver, T. S., and Green, L. (2011). Domain independence and stability in young and older adults' discounting of delayed rewards. *Behav. Processes* 87, 253–259.

Karbach, J., and Kray, J. (2009). How useful is executive control training? Age differences in near and far transfer of task-switching training. *Dev. Sci.* 12, 978–990.

Karbach, J., Mang, S., and Kray, J. (2010). Transfer of task-switching training in older age: the role of verbal processes. *Psychol. Aging* 25, 677–683.

Karp, A., Paillard-Borg, S., Wang, H. X., Silverstein, M., Winblad, B., and Fratiglioni, L. (2006). Mental, physical and social components in leisure activities equally contribute to decrease dementia risk. *Dement. Geriatr. Cogn. Disord.* 21, 65–73.

Kempermann, G., Gast, D., and Gage, F. H. (2002). Neuroplasticity in old age: sustained fivefold induction of hippocampal neurogenesis by long-term environmental enrichment. *Ann. Neurol.* 52, 135–143.

Kliegel, M., and Bürki, C. (2012). Memory training interventions require a tailor-made approach: commentary on McDaniel and Bugg. *J. Appl. Res. Mem. Cogn.* 1, 58–60.

Kliegl, R., Smith, J., and Baltes, P. B. (1989). Testing-the-limits and the study of adult age differences in cognitive plasticity of a mnemonic skill. *Dev. Psychol.* 25, 247–256.

Klostermann, E. C., Braskie, M. N., Landau, S. M., O'neil, J. P., and Jagust, W. J. (2011). Dopamine and frontostriatal networks in cognitive aging. *Neurobiol. Aging* 33, 623.e615– 623.e624.

Kochunov, P., Coyle, T., Lancaster, J., Robin, D. A., Hardies, J., Kochunov, V., Bartzokis, G., Stanley, J., Royall, D., Schlosser, A. E., Null, M., and Fox, P. T. (2010). Processing speed is correlated with cerebral health markers in the frontal lobes as quantified by neuroimaging. *Neuroimage* 49, 1190–1199.

Kramer, A. F., Hahn, S., and Gopher, D. (1999). Task coordination and aging: explorations of executive control processes in the task switching paradigm. *Acta Psychol. (Amst.)* 101, 339–378.

Kray, J., Eber, J., and Karbach, J. (2008). Verbal self-instructions in task switching: a compensatory tool for action-control deficits in childhood and old age? *Dev. Sci.* 11, 223–236.

Kray, J., and Lindenberger, U. (2000). Adult age differences in task switching. *Psychol. Aging* 15, 126–147.

Landau, S. M., Lal, R., O'neil, J. P., Baker, S., and Jagust, W. J. (2009). Striatal dopamine and working memory. *Cereb. Cortex* 19, 445–454.

Li, K. Z. H., Roudaia, E., Lussier, M., Bherer, L., Leroux, A., and McKinley, P. (2010). Benefits of cognitive dual-task training on balance performance in healthy older adults. *J. Gerontol. A Biol. Sci. Med. Sci.* 65, 1344.

Li, S. C., Schmiedek, F., Huxhold, O., Röcke, C., Smith, J., and Lindenberger, U. (2008). Working memory plasticity in old age: practice gain, transfer, and maintenance. *Psychol. Aging* 23, 731.

Lindenberger, U., Nagel, I. E., Chicherio, C., Li, S. C., Heekeren, H. R., and Bäckman, L. (2008). Age-related decline in brain resources modulates genetic effects on cognitive functioning. *Front. Neurosci.* 2, 234–244. doi: 10.3389/neuro.01.039.2008

Liu, T., Wen, W., Zhu, W., Kochan, N. A., Trollor, J. N., Reppermund, S., Jin, J. S., Luo, S., Brodaty, H., and Sachdev, P. S. (2011). The relationship between cortical sulcal variability and cognitive performance in the elderly. *Neuroimage* 56, 865–873.

Löckenhoff, C. E., O'donoghue, T., and Dunning, D. (2011). Age differences in temporal discounting: the role of dispositional affect and anticipated emotions. *Psychol. Aging* 26, 274.

Logie, R. H., Cocchini, G., Delia Sala, S., and Baddeley, A. D. (2004). Is there a specific executive capacity for dual task coordination? Evidence from Alzheimer's disease. *Neuropsychology* 18, 504–513.

Luo, L., and Craik, F. I. (2008). Aging and memory: a cognitive approach. *Can. J. Psychiatry* 53, 346–353.

Lustig, C., and Flegal, K. E. (2008). Targeting latent function: encouraging effective encoding for successful memory training and transfer. *Psychol. Aging* 23, 754–764.

Lustig, C., Shah, P., Seidler, R., and Reuter-Lorenz, P. A. (2009). Aging, training, and the brain: a review and future directions. *Neuropsychol. Rev.* 19, 504–522.

Madden, D. J., Bennett, I. J., and Song, A. W. (2009). Cerebral white matter integrity and cognitive aging: contributions from diffusion tensor imaging. *Neuropsychol. Rev.* 19, 415–435.

Mahncke, H. W., Connor, B. B., Appelman, J., Ahsanuddin, O. N., Hardy, J. L., Wood, R. A., Joyce, N. M., Boniske, T., Atkins, S. M., and Merzenich, M. M. (2006). Memory enhancement in healthy older adults using a brain plasticity-based training program: a randomized, controlled study. *Proc. Natl. Acad. Sci. U.S.A.* 103, 12523–12528.

Manuel, A. L., Grivel, J., Bernasconi, F., Murray, M. M., and Spierer, L. (2010). Brain dynamics underlying training-induced improvement in suppressing inappropriate action. *J. Neurosci.* 30, 13670.

Marks, B. L., Madden, D. J., Bucur, B., Provenzale, J. M., White, L. E., Cabeza, R., and Huettel, S. A. (2007). Role of aerobic fitness and aging on cerebral white matter integrity. *Ann. N.Y. Acad. Sci.* 1097, 171–174.

Mata, R., Josef, A. K., Samanez-Larkin, G. R., and Hertwig, R. (2011). Age differences in risky choice: a meta-analysis. *Ann. N.Y. Acad. Sci.* 1235, 18–29.

Mata, R., and Nunes, L. (2010). When less is enough: cognitive aging, information search, and decision quality in consumer choice. *Psychol. Aging* 25, 289.

Maylor, E. A., Birak, K. S., and Schlaghecken, F. (2011). Inhibitory motor control in old age: evidence for de-automatization? *Front. Psychol.* 2:132. doi: 10.3389/fpsyg.2011.00132

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., and Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "Frontal Lobe" tasks: a latent variable analysis. *Cogn. Psychol.* 41, 49–100.

Mohr, P. N. C., Li, S. C., and Heekeren, H. R. (2010). Neuroeconomics and aging: neuromodulation of economic decision making in old age. *Neurosci. Biobehav. Rev.* 34, 678–688.

Moody, D. E. (2009). Can intelligence be increased by training on a task of working memory? *Intelligence* 37, 327–328.

Nieuwenhuis, S., Ridderinkhof, K. R., De Jong, R., Kok, A., and Van Der Molen, M. W. (2000). Inhibitory inefficiency and failures of intention activation: age-related decline in the control of saccadic eye movements. *Psychol. Aging* 15, 635–647.

Noack, H., Lövden, M., Schmiedek, F., and Lindenberger, U. (2009). Cognitive plasticity in adulthood and old age: gauging the generality of cognitive intervention effects. *Restor. Neurol. Neurosci.* 27, 435–453.

O'brien, J. L., O'keefe, K. M., Laviolette, P. S., Deluca, A. N., Blacker, D., Dickerson, B. C., and Sperling, R. A. (2010). Longitudinal fMRI in elderly reveals loss of hippocampal activation with clinical decline. *Neurology* 74, 1969–1976.

O'sullivan, M., Jones, D. K., Summers, P. E., Morris, R. G., Williams, S. C., and Markus, H. S. (2001). Evidence for cortical "disconnection" as a mechanism of age-related cognitive decline. *Neurology* 57, 632–638.

Papp, K. V., Walsh, S. J., and Snyder, P. J. (2009). Immediate and delayed effects of cognitive interventions in healthy elderly: a review of current literature and future directions. *Alzheimers Dement.* 5, 50–60.

Persson, J., Nyberg, L., Lind, J., Larsson, A., Nilsson, L. G., Ingvar, M., and Buckner, R. L. (2006). Structure–function correlates of cognitive decline in aging. *Cereb. Cortex* 16, 907.

Potter, G. G., Helms, M. J., Burke, J. R., Steffens, D. C., and Plassman, B. L. (2007). Job demands and dementia risk among male twin pairs. *Alzheimers Dement.* 3, 192–199.

Rabbitt, P., Lowe, C., and Shilling, V. (2001). Frontal tests and models for cognitive ageing. *Eur. J. Cogn. Psychol.* 13, 5–28.

Ranganath, C., and Rainer, G. (2003). Neural mechanisms for detecting and remembering novel events. *Nat. Rev. Neurosci.* 4, 193–202.

Raz, N., Lindenberger, U., Rodrigue, K. M., Kennedy, K. M., Head, D., Williamson, A., Dahle, C., Gerstorf, D., and Acker, J. D. (2005). Regional brain changes in aging healthy adults: general trends, individual differences and modifiers. *Cereb. Cortex* 15, 1676–1689.

Rebok, G. W., Carlson, M. C., and Langbaurn, J. B. S. (2007). Training and maintaining memory abilities in healthy older adults: traditional and novel approaches. *J. Gerontol. B Psychol. Sci. Soc. Sci.* 62, 53–61.

Reimers, S., Maylor, E. A., Stewart, N., and Chater, N. (2009). Associations between a one-shot delay discounting measure and age, income, education and real-world impulsive behavior. *Pers. Individ. Dif.* 47, 973–978.

Ridderinkhof, K. R., Forstmann, B. U., Wylie, S. A., Burle, B., and Van Den Wildenberg, W. P. M. (2011). Neurocognitive mechanisms of action control: resisting the call of the sirens. *Wiley Interdiscip. Rev. Cogn. Sci.* 2, 174–192.

Ridderinkhof, K. R., Van Den Wildenberg, W. P. M., Segalowitz, S. J., and Carter, C. S. (2004). Neurocognitive mechanisms of cognitive control: the role of prefrontal cortex in action selection, response inhibition, performance monitoring, and reward-based learning. *Brain Cogn.* 56, 129–140.

Roberts, B. A., Fuhrer, R., Marmot, M., and Richards, M. (2011). Does retirement influence cognitive performance? the whitehall II study. *J. Epidemiol. Community Health* 65, 958–963.

Salmon, E., Van Der Linden, M., Collette, F., Delfiore, G., Maquet, P., Degueldre, C., Luxen, A., and Franck, G. (1996). Regional brain activity during working memory tasks. *Brain* 119(Pt 5), 1617–1625.

Samanez-Larkin, G. R., Gibbs, S. E., Khanna, K., Nielsen, L., Carstensen, L. L., and Knutson, B. (2007). Anticipation of monetary gain but not loss in healthy older adults. *Nat. Neurosci.* 10, 787–791.

Samanez-Larkin, G. R., Wagner, A. D., and Knutson, B. (2011). Expected value information improves financial risk taking across the adult life span. *Soc. Cogn. Affect. Neurosci.* 6, 207.

Schliebs, R., and Arendt, T. (2010). The cholinergic system in aging and neuronal degeneration. *Behav. Brain Res.* 221, 555–563.

Schmiedek, F., Lövdén, M., and Lindenberger, U. (2010). Hundred days of cognitive training enhance broad cognitive abilities in adulthood: findings from the COGITO study. *Front. Aging Neurosci.* 2:27. doi: 10.3389/fnagi.2010.00027

Schmitt-Eliassen, J., Ferstl, R., Wiesner, C., Deuschl, G., and Witt, K. (2007). Feedback-based versus observational classification learning in healthy aging and Parkinson's disease. *Brain Res.* 1142, 178–188.

Schooler, C., Mulatu, M. S., and Oates, G. (1999). The continuing effects of substantively complex work on the intellectual functioning of older workers. *Psychol. Aging* 14, 483–506.

Schott, B. H., Niehaus, L., Wittmann, B. C., Schutze, H., Seidenbecher, C. I., Heinze, H. J., and Düzel, E. (2007). Ageing and early-stage Parkinson's disease affect separable neural mechanisms of mesolimbic reward processing. *Brain* 130, 2412–2424.

Sharps, M. J., and Price-Sharps, J. L. (1996). Visual memory support: An effective mnemonic device for older adults. *Gerontologist* 36, 706–708.

Shipstead, Z., Redick, T. S., and Engle, R. W. (2010). Does working memory training generalize? *Psychol. Belg.* 50, 245–276.

Smith, G. E., Housen, P., Yaffe, K., Ruff, R., Kennison, R. F., Mahncke, H. W., and Zelinski, E. M. (2009). A cognitive training program based on principles of brain plasticity: results from the improvement in memory with plasticity-based adaptive cognitive training (IMPACT) study. *J. Am. Geriatr. Soc.* 57, 594–603.

Stigsdotter, A., and Bäckman, L. (1989). Multifactorial memory training with older adults - how to foster maintenance of improved performance. *Gerontology* 35, 260–267.

Strobach, T., Liepelt, R., Schubert, T., and Kiesel, A. (2011). Task switching: effects of practice on switch and mixing costs. *Psychol. Res.* 76, 74–83.

Thorell, L. B., Lindqvist, S., Nutley, S. B., Bohlin, G., and Klingberg, T. (2009). Training and transfer effects of executive functions in preschool children. *Dev. Sci.* 12, 106–113.

Treitz, F. H., Heyder, K., and Daum, I. (2007). Differential course of executive control changes during normal aging. *Neuropsychol. Dev. Cogn. B Aging Neuropsychol. Cogn.* 14, 370–393.

Van Der Linden, M., Collette, F., Salmon, E., Delfiore, G., Degueldre, C., Luxen, A., and Franck, G. (1999). The neural correlates of updating information in verbal working memory. *Memory* 7, 549–560.

Van Gerven, P. W., Meijer, W. A., Prickaerts, J. H., and Van Der Veen, F. M. (2008). Aging and focus switching in working memory: excluding the potential role of memory load. *Exp. Aging Res.* 34, 367–378.

Verhaeghen, P., and Basak, C. (2005). Ageing and switching of the focus of attention in working memory: results from a modified N-back task. *Q. J. Exp. Psychol. A* 58, 134–154.

Verhaeghen, P., Steitz, D. W., Sliwinski, M. J., and Cerella, J. (2003). Aging and dual-task performance: a meta-analysis. *Psychol. Aging* 18, 443–460.

Volkow, N. D., Gur, R. C., Wang, G. J., Fowler, J. S., Moberg, P. J., Ding, Y. S., Hitzemann, R., Smith, G., and Logan, J. (1998). Association between decline in brain dopamine activity with age and cognitive and motor impairment in healthy individuals. *Am. J. Psychiatry* 155, 344–349.

Voss, M. W., Prakash, R. S., Erickson, K. I., Basak, C., Chaddock, L., Kim, J. S., Alves, H., Heo, S., Szabo, A. N., and White, S. M. (2010). Plasticity of brain networks in a randomized intervention trial of exercise training in older adults. *Front. Aging Neurosci.* 2:32. doi: 10.3389/fnagi.2010.00032

Waiter, G. D., Fox, H. C., Murray, A. D., Starr, J. M., Staff, R. T., Bourne, V. J., Whalley, L. J., and Deary, I. J. (2008). Is retaining the youthful functional anatomy underlying speed of information processing a signature of successful cognitive ageing? An event-related fMRI study of inspection time performance. *Neuroimage* 41, 581–595.

Wang, G. J., Volkow, N. D., Logan, J., Fowler, J. S., Schlyer, D., Macgregor, R. R., Hitzemann, R. J., Gur, R. C., and Wolf, A. P. (1995). Evaluation of age-related changes in serotonin 5-HT2 and dopamine D2 receptor availability in healthy human subjects. *Life Sci.* 56, PL249–PL253.

Wang, Y., Chan, G. L., Holden, J. E., Dobko, T., Mak, E., Schulzer, M., Huser, J. M., Snow, B. J., Ruth, T. J., Calne, D. B., and Stoessl, A. J. (1998). Age-dependent decline of dopamine D1 receptors in human brain: a PET study. *Synapse* 30, 56–61.

Wecker, N. S., Kramer, J. H., Hallam, B. J., and Delis, D. C. (2005). Mental flexibility: age effects on switching. *Neuropsychology* 19, 345–352.

Williams, B. R., Ponesse, J. S., Schachar, R. J., Logan, G. D., and Tannock, R. (1999). Development of inhibitory control across the life span. *Dev. Psychol.* 35, 205.

Winocur, G. (1998). Environmental influences on cognitive decline in aged rats. *Neurobiol. Aging* 19, 589–597.

Yaffe, K., Fiocco, A. J., Lindquist, K., Vittinghoff, E., Simonsick, E. M., Newman, A. B., Satterfield, S., Rosano, C., Rubin, S. M., Ayonayon, H. N., and Harris, T. B. (2009). Predictors of maintaining cognitive function in older adults: the health ABC study. *Neurology* 72, 2029–2035.

Yates, F. (1966). *The Art of Memory.* London: Routledge and Kegan Paul Ltd.

Zelinski, E. M. (2009). Far transfer in cognitive training of older adults. *Restor. Neurol. Neurosci.* 27, 455–471.

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Training-induced improvement of response selection and error detection in aging assessed by task switching: effects of cognitive, physical, and relaxation training

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Cognitive control functions decline with increasing age. The present study examines if different types of group-based and trainer-guided training effectively enhance performance of older adults in a task switching task, and how this expected enhancement is reflected in changes of cognitive functions, as measured in electrophysiological brain activity (event-related potentials). One hundred forty-one healthy participants aged 65 years and older were randomly assigned to one of four groups: physical training (combined aerobic and strength training), cognitive training (paper–pencil and computer-aided), relaxation and wellness (social control group), and a control group that did not receive any intervention. Training sessions took place twice a week for 90 min for a period of 4 months. The results showed a greater improvement of performance for attendants of the cognitive training group compared to the other groups. This improvement was evident in a reduction of mixing costs in accuracy and intraindividual variability of speed, indexing improved maintenance of multiple task sets in working memory, and an enhanced coherence of neuronal processing. These findings were supported by event-related brain potentials which showed higher amplitudes in a number of potentials associated with response selection (N2), allocation of cognitive resources (P3b), and error detection (Ne). Taken together, our findings suggest neurocognitive plasticity of aging brains which can be stimulated by broad and multilayered cognitive training and assessed in detail by electrophysiological methods.

Keywords: aging, cognitive training, physical training, task switching, response selection, ERPs, N2, Ne

INTRODUCTION

The primary role of executive or control functions is planning, maintaining, and implementing of goal-directed behavior. This behavior requires a number of distinct cognitive abilities like working memory, selective attention, multitasking, task switching, response monitoring, and error detection. Nearly all of these functions show an age-related decline (Craik and Salthouse, 2000; Band and Kok, 2000; Falkenstein et al., 2000, 2001, 2002; Kray and Lindenberger, 2000; Verhaeghen and Cerella, 2002; Salthouse, 2009). However, the decay of these functions is extremely different among individuals, and some of them preserve a high functional level until very old age whereas other's cognitive abilities decrease already in the middle of adolescence (Baltes and Lindenberger, 1997; Hultsch and MacDonald, 2004). Thus, the investigation of factors preventing cognitive decline, the development of methods for compensation as well as interventions to improve fluid cognition in elderly plays a crucial role for maintaining quality of life in older age.

Indeed, in recent years, there is an increasing interest in factors ameliorating cognitive and brain aging. Whereas genetic dispositions set an individual range of cognitive abilities, which are even magnified in late relative to early adulthood (Lindenberger et al., 2008), variable factors like nutrition or level of physical, social, and cognitive engagement can provide stimulation of the cognitive system that can reduce some age-related deficits (Bielak et al., 2007; see also Greenwood and Parasuraman, 2010 and Gajewski and Falkenstein, 2011a for reviews).

The most consistent improvements of control functions in older age were found after physical exercise (see Colcombe and Kramer, 2003; Kramer and Erickson, 2007; Hillman et al., 2008, for reviews). For example, Colcombe et al. (2004) showed that older participants improved performance in an executive function task and showed larger activation in brain areas supporting these functions after a 6-month cardiovascular training. Smiley-Oyen et al. (2008) compared effects of aerobic and strength training in older persons on executive control tasks and found largest benefits of the aerobic training after 5 months training. Similar effects on executive functions in elderly were reported by Liu-Ambrose et al. (2010) after 1 year resistance training. Recently, Voelcker-Rehage et al. (2011) reported differential effects of 1 year cardiovascular and coordination training on executive control and perceptual speed tasks as well as effects on the underlying brain activity measured by fMRT. These findings suggest that not only aerobic training but also other types of physical activity are beneficial regarding cognitive functions. Thus, combination of different types of training like aerobic and strength exercises may be more beneficial than only one type as different neuronal structures are involved (Colcombe and Kramer, 2003; Heyn et al., 2004; Kramer et al., 2006). Indeed, Colcombe and Kramer (2003) and McAuley et al. (2004) argued that a combined cardiovascular and strength training would be most promising regarding cognitive improvements. The neuronal mechanisms of aerobic exercise on executive functions are not entirely clear but animal and human research suggest enhanced neurogenesis and synaptic plasticity stimulated by higher concentrations of brain-derived neurothrophic factor (BDNF), particularly in the hippocampus, a brain area strongly associated with learning and memory (van Praag et al., 1999, 2005; Wiskott et al., 2006; Erickson et al., 2011; Gajewski et al., 2011).

A second possibility to enhance cognitive functions in aging is formal cognitive training that focuses either on one domain only, for example memory (Klingberg et al., 2002; Jaeggi et al., 2008), attention (Green and Bavelier, 2003), visual search (Becic et al., 2008), dual task (Bherer et al., 2005), or task switching (Minear and Shah, 2008; Karbach and Kray, 2009). In the earlier studies the training effects were indeed restricted to the trained function and did not transfer to other functions or daily activities (e.g., Willis and Schaie, 1986; Ball et al., 2002; Dahlin et al., 2009) while other reports showed also transfer effects to non-trained functions (e.g., Gopher et al., 1994; Klingberg et al., 2005; Willis et al., 2006; Ball et al., 2007; Caserta et al., 2007; Basak et al., 2008; Cassavaugh and Kramer, 2009; Edwards et al., 2009; Karbach and Kray, 2009; Klusmann et al., 2010; Jaeggi et al., 2011). As claimed by Kramer and Morrow (in press) and Hertzog et al. (2008) it may be important to design cognitive training interventions that are not limited to a single process (such as reasoning or processing speed) but instead incorporate a number of processes in the training program in order to maximize the general training gains. Accordingly, such a multidomain cognitive training may enhance the probability to observe transfer effects to non-trained or even daily life functions.

Multidomain training also provides novelty, which most likely stimulates brain plasticity (Düzel et al., 2010). Finally, multidomain training avoids monotony and enhances fun and the motivation to train. Hence it appears promising to conduct a multidomain training that involves several fluid functions in order to reach a cross-functional effect and elevate the probability for transfer to other areas or even to daily life activities (Kramer and Morrow, in press). Such training can be a complex videogame (Basak et al., 2008) or a mixture of training tasks which altogether covers most fluid functions.

A third possibility for stimulating cognition is an interaction in a social group and new experiences in general, which are known to stimulate neuroprotective effects in animal and human studies (Kempermann et al., 1997; Hultsch et al., 1999; Frick and Fernandez, 2003; Singh-Manoux et al., 2003; Milgram et al., 2006; Bielak et al., 2007; Hertzog et al., 2009; Swaab and Bao, 2011). Thus, the influence of group interactions as such has to be controlled.

Longitudinal studies examining training-induced changes of neuronal activity underlying the performance changes are rather sparse. Most of them investigated effects of cardiovascular training (Colcombe et al., 2004; Voelcker-Rehage et al., 2011). To our knowledge, effects of a longitudinal cognitive training on neuroelectrical activity in elderly people have not yet been analyzed. However, it could be assumed that cognitive training reflects a form of learning and acquiring of expertise including changes of neuronal networks (Lustig et al., 2009). As has been shown repeatedly, new experiences or managing of unusual complex situations are accompanied by synaptic plasticity and neurogenesis (Milgram et al., 2006; Whitlock et al., 2006; Greenwood, 2007; Pereira et al., 2007; Greenwood and Parasuraman, 2010; Swaab and Bao, 2011). A number of studies investigating neuronal correlates of simple perceptual or memory training in humans showed changes in the volume of gray matter (Ilg et al., 2008), white matter (Takeuchi et al., 2010), and cerebral blood flow (Mozolic et al., 2010) but also in electrical brain activity (e.g., Reinke et al., 2003; Roche and O'Mara, 2003; Song et al., 2005; Tong et al., 2009). It is likely that these phenomena are not independent and reflect consequences of a number of neurobiological adaptation processes. Training inducing plastic brain changes can also be observed in advanced age (Jones et al., 2006; Greenwood, 2007; Greenwood and Parasuraman, 2010; Zehnder et al., 2009, for reviews).

THE PRESENT STUDY

As mentioned above, there is, to our knowledge, by now no longitudinal study that investigated changes in electrical brain activity due to cognitive and physical training in older subjects. Thus, the present study aims at investigating the impact of a multidomain physical and a multidomain cognitive training on fluid cognitive and brain functions relative to a relaxation group as well as a no-contact control group. The training-related neurocognitive changes were assessed by a PC-based task switching paradigm and associated electrophysiological parameters.

By using the task switching paradigm specific functions like maintaining, selecting, and switching between multiple task sets can be analyzed as a function of aging (Kramer et al., 1999; Kray and Lindenberger, 2000; Cepeda et al., 2001; De Jong, 2001; Mayr, 2001; Mayr and Liebscher, 2001; Meiran et al., 2001; Kray et al., 2004; Kray, 2006; West and Travers, 2008). The role of the response selection and monitoring system is to translate the goals into action and to control the outcome in order to prevent possible errors. This function is strongly loaded during task switching and even more in switch trials than in repeat trials (Gajewski et al., 2010a).

Crucial behavioral outcomes of the task switching paradigm are so called *mixing costs*, defined as the difference between non-switch trials in mixed and single task blocks and *local switch costs*, defined as a difference between performance in task switch trials and non-switch trials (Allport et al., 1994; Rogers and Monsell, 1995; Meiran, 1996). Mixing costs are assumed to represent retrieval and active maintenance of multiple task sets in memory, whereas local costs are rather attributed to proactive interference between previously and the currently relevant task (see Kiesel et al., 2010 for overview). Mixing costs are consistently found to be enhanced in older age, whereas local costs usually do not differ between younger and older participants (e.g., Kramer et al., 1999; Kray and Lindenberger, 2000; Cepeda et al., 2001; Mayr, 2001; Kray, 2006; Gajewski et al., 2010b).

Some studies investigated intraindividual variability in speed performance as it has been shown that the variability is a valid behavioral indicator of neuronal integrity, which is declined in age (Hultsch and MacDonald, 2004). Thus, beside reaction times and error rates we analyzed this parameter to obtain possible training-related decrease of intra-personal variability (Ram et al., 2005).

Event-related potentials (ERPs) offer additional insights in the electrophysiological mechanisms underlying task switching. As ERPs have an excellent time resolution, there is the possibility to analyze each sub-process involved in task switching. In the present study we focused on controlled and executive processes in task switching, namely response selection and error detection. In particular, we analyzed response selection as reflected in the N2 (Ritter et al., 1979, 1982, 1983; Towey et al., 1980; Gajewski et al., 2008, 2010a, 2011) and error detection as reflected in the Ne or ERN (Falkenstein et al., 1991; Gehring et al., 1993; Band and Kok, 2000; Falkenstein et al., 2000, 2001; Kolev et al., 2005). In addition the P3b was analyzed as a classical measure of working memory resources or more generally the processing capacity (Donchin, 1981; Donchin and Coles, 1988; Kok, 2001; Polich, 2007; Gajewski et al., 2010b; Gajewski and Falkenstein, 2011b).

As it has been shown that electrophysiological brain activity is enhanced by short-term training in different domains, we assume that some of the functions reflected in the ERPs will also be improved by a long-term cognitive and/or physical training. Thus, the electrophysiological markers should help to differentiate which processes are changed due to training and which are not. In particular, we expect enhancement of processing capacity as reflected in the P3b and response selection as reflected in the N2. Moreover, a more efficient response selection may also improve error detection, which should be reflected in an increase of the error negativity (Ne). Consequently, performance improvements on behavioral level should be apparent in lower mixing and/or switch costs, in speed and/or accuracy, as previously shown (Karbach and Kray, 2009). An additional performance parameter reflecting the efficiency of task-related processing is the intraindividual variability of reaction times. A reduced variability of speed is assumed to reflect an increased coherence of neuronal processing (Hultsch and MacDonald, 2004), which appears in a more precise timing of response selection.

Since cognitive stimulation may also be induced by social interactions within a group, we included in the design two control groups: a social control group without cognitive demands in the contents, and a passive control group without group contact. To this end, 152 participants were randomly assigned to one of four groups: physical training, cognitive training, relaxation training (social control), and passive control (no-contact) group. Participants were trained for 4 months, two times per week, and 90 min per session. The cognitive training group received a multidomain paper and pencil and PC-based training, which, however, did not include a task switching training. The cognitive training was combined from cheap or freely available training packages. The physical training group received a multidomain, circular cardiovascular, strength, and aerobic training. The relaxation group conducted easy stretching, relaxation exercises, and autogenic training that were cognitively non-demanding, while the passive control group did not receive any intervention but was simply measured with respect to cognitive functions at about the same time as the active groups. In summary, all three active groups received a multifaceted physical or cognitive or wellness training, while the no-contact group received no intervention.

MATERIALS AND METHODS

PARTICIPANTS

Participants were recruited through a number of newspaper advertisements and flyers distributed in the city of Dortmund (Germany). Participants were included in the study after meeting some criteria inquired by a telephone interview. They should be 65 or older, physically and mentally fit, living independently and self-paced (no nursing home), and having sufficient or corrected visual and auditory acuity. Exclusion criterions were: history of cardiovascular, psychiatric, neurological, motor or oncologic diseases, and psychopharmacologic or hormonal therapy. Moreover, participants were not included if they already did train physically (jogging, walking, swimming, dancing, fitness center) or cognitively (e.g., memory training) more than 1.5 h weekly. Finally, they were asked whether they planned some travels or other activities in the next 6 months that would avoid regular training participation. Four hundred sixty-seven telephone interviews were completed, 152 persons met the criteria and were included in the study. Eleven participants dropped out during the study. Consequently, 141 participants constituted the final sample (**Table 1**).

The participants received 100 Euro at the end of the study to compensate their travel expenses. The study was approved by the local ethics committee of the Leibniz association and its accordance with the declaration of Helsinki. The scope of the study was explained to all participants and they were given a written informed consent before any study protocol was commenced. The groups were comparable in all socio-demographic, cognitive, personality, and physical variables presented in **Table 1** as no significant differences were found.

TRAININGS

Participants were randomly assigned to one of four groups: physical, cognitive, and relaxation training and a control group. Participants were trained for 4 months, two times per week and 90 min per session. All trainings were supervised by professional trainers.

Physical training consisted of cardiovascular, aerobic, and strength exercises which were done to the same amount within each session. The cardiovascular training was conducted using treadmills, bicycle ergometers, and cross trainers which included pulse meters in order to control the heart function permanently. The aerobic exercises consisted of a number of easy step and floor movement sequences. The muscular strength exercises were conducted using strength machines as a combination of eight different sets which were repeated in 3×15 series by performing oppose muscle contraction. These exercises aimed at strengthening skeletal muscles and increasing the metabolism. Intensity of the training units was continuously increased but regarded the individual capability of the participants.

The multidomain cognitive training included paper and pencil and PC-based exercises. In the first 4 weeks the “Mental Activation Training” (MAT; Lehrl et al., 1994) and sudoku were used. Additionally, in the first eight sessions participants without any PC-experience were made step by step familiar with the computer handling. In the following weeks, the participants exercised using selected commercial and non-commercial internet-based software. The difficulty level of the exercises was continuously adapted to the individual abilities of the participants.

Table 1 | Socio-demographic characteristics of the whole sample and separated for each experimental (physical, cognitive) and control (relaxation, no-contact) group.

	Total	Physical	Cognitive	Relaxation	Control
N	141	35	32	34	40
Age	70.9 (5.2)	71.9 (7.4)	70.9 (4.1)	71.1 (4.5)	69.9 (4.2)
Above 70 (%)	51.4	51.4	53.1	57.1	45.0
SEX (%)					
Male	40.1	42.9	37.5	40.0	40.0
FAMILY STATUS					
Single (%)	7.0	11.4	15.6	2.9	0.0
Married (%)	52.1	60.0	46.9	57.1	45.0
Divorced (%)	18.3	8.6	25.0	14.3	25.0
Widowed (%)	21.1	17.1	12.5	25.7	27.5
Partnership (%)	1.4	2.9	0.0	0.0	2.5
EDUCATIONAL DEGREE					
No degree (%)	2.9	0.0	6.5	2.9	2.6
Primary (%)	37.7	38.2	22.6	52.9	35.9
Secondary general (%)	2.9	5.9	3.2	2.9	0.0
Intermediate secondary (%)	29.0	23.5	41.9	20.6	30.8
Gymnasium (%)	27.5	32.4	25.8	20.6	30.8
Years of occupation	34.2 (12.7)	34.9 (14.2)	35.5 (12.9)*	34.0 (12.1)*	32.7 (11.9)*
MMSE	28.5 (1.7)	28.5 (1.3)	28.8 (1.9)	28.5 (1.6)	28.1 (2.0)
IQ (MWT-B)	116.3 (12.1)	114.6 (10.4)	116.0 (11.3)	116.0 (12.5)	118.2 (13.8)
BDI	5 (3.7)	6.2 (4.4)	4.7 (3.5)	4.7 (3.5)	4.5 (3.3)
NEO-FFI					
Neuroticism	17.6 (5.7)	17.6 (6.7)	16.3 (5.5)	18.2 (5.1)	18.4 (5.6)
Extraversion	25.1 (6.2)	24.7 (6.5)	26.7 (6.7)	25.3 (5.0)	24.1 (6.5)
Openess to experience	25.7 (6.8)	25.2 (7.1)	29.3 (5.9)	23.7 (7.0)	25.1 (6.3)
Agreeableness	26.8 (7.5)	27.8 (6.4)	29.0 (8.1)	24.9 (7.6)	26.0 (7.6)
Conscientiousness	30.8 (6.4)	30.6 (6.3)	32.6 (5.7)	30.8 (7.1)	29.5 (6.2)
WHOQOL-BREF					
Physical health	16.0 (1.9)	15.7 (2.1)	16.4 (1.6)	15.6 (2.1)	16.3 (1.8)
Psychological	14.5 (1.5)	14.5 (1.4)	14.3 (1.9)	14.2 (1.5)	14.9 (1.1)
Social relationships	14.7 (2.0)	14.6 (2.3)	14.7 (1.9)	14.2 (1.8)	15.1 (1.9)
Environment	16.0 (1.5)	15.5 (1.5)	16.3 (1.6)	15.9 (1.5)	16.3 (1.4)
PHYSICAL ACTIVITY					
Strolling (min/week)	174.3	166.1	155.0	172.2	197.8
Dancing (min/month)	36.6	46.8	24.0	33.6	40.2
Bowling (min/month)	21	25.8	17.4	18.6	21
Swimming (min/month)	68.7	73.2	51	100.9	49.7
Walking (min/week)	34.4	24.6	19.2	17.1	69.8
Ergometry (Watt)	96.2 (31.3)	96.1 (32.7)	90.9 (32.4)	102.8 (31.5)	95.0 (29.1)
Body mass index (BMI)	26.6 (4.4)	26.9 (4.3)	26.8 (4.5)	26.6 (4.34)	26.0 (4.5)
No occupation of some participants*		$n = 31$*	$n = 28$*	$n = 37$*	

Distribution of some characteristics across the groups is presented in (%), remaining values represent means and standard deviations in parentheses. Mini Mental State Examination (MMSE; Folstein et al., 1975), Multiple-choice vocabulary test (MWT-B; Lehrl et al., 1995), Becks Depression Inventory (BDI; Beck et al., 1961), WHO-Quality of Life-BREF (WHOQOL Group, 1998), NEO-FFI ("Big Five" personality factors questionnaire; Costa and McCrae, 1992).

Each session consisted of different exercises that aimed at training crucial cognitive functions. The exercises mainly trained perceptual speed, attentional, and mnemonic functions but some exercises included reasoning or logical thinking. A detailed description of all used exercises and a schedule of the training program are given in the Appendix.

No explicit task switching exercise was included in this program. Two extra sessions were offered at the end of the program for those participants who missed the regular sessions. The participants were not encouraged to exercise outside the training sessions but to continue the training at home after the study was finished.

The relaxation group received a relaxation training consisting of autogenic training, progressive muscle relaxation, back training, breathing exercises, massage, and Qigong. The aim of this training was to provide interesting and varied exercises, which did hardly require, and hence should not train, cognitive functions.

TESTING

Participants completed several questionnaires at home which they brought to the test session. During the testing a number of paper and pencil and computerized psychometric tasks were applied.

STIMULI AND TASKS

Stimuli consisted of the digits 1–9, excluding the number 5. The digits were white presented on a black computer screen 3 mm above the white fixation point (10 mm diameter). Each digit was either small (7 mm × 10 mm) or large (12 mm × 18 mm). A cue stimulus (16 mm × 32 mm) indicating the relevant task was presented 3 mm below the fixation point. The cue "NUM" (German "Numerisch," numeric) indicated a numerical task (greater or less than 5), "GER" (German "Geradzahligkeit," parity) the parity task (odd vs. even), "SCH" (German "Schrift," font) the font-size task (small vs. large).

Responses consisted of pressing one of two buttons which were mounted in a response box. The buttons should be pressed with the index fingers.

The stimulus–response mapping of the three tasks was overlapping, that is, responses according to "smaller than five," "even," and "small size" were assigned to the left key and "larger than five," "odd," and "large size" to the right key. This assignment was counterbalanced across participants.

PROCEDURE

A schematic example of a trial is shown in **Figure 1**.

A trial started with a presentation of the fixation point. A cue stimulus that indicated the relevant task in advance was presented for 1300 ms which remained visible when the digit was presented. A response had to be given within 2500 ms after target onset. Five hundred milliseconds after the response a feedback was displayed for 500 ms. In case of a correct response a plus sign, after a wrong response a minus sign was displayed. The response–cue interval (RCI) was set to 1000 ms and included the response-feedback delay and the feedback.

At the beginning of the session participants performed three single task blocks with a fixed task NUM, GER, and SCH consisting of 34 trials each. Afterward, the participants performed an exercise block with 16 trials including all three tasks, followed by the mixed block (124 trials). The frequency of task switch in the cue-based block amounted to 50%. The order of the trials was random. The participants were given a written instruction that explained the task. The instruction encouraged quick and accurate responses.

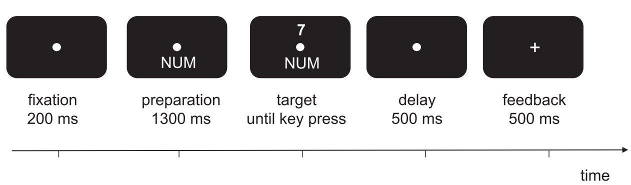

FIGURE 1 | Schematic illustration of a trial.

ERP RECORDINGS

EEG was recorded continuously from 32 scalp electrodes according to the extended 10–20 system (Jasper, 1958) and mounted on an elastic cap. The montage included 8 midline sites and 12 sites on each hemisphere and two mastoid electrodes (M1 and M2). The EEG was re-referenced offline to linked mastoids. The horizontal and vertical EOG was recorded bipolarly from electrodes at both eyes. Eye movement artifacts were corrected using the correction algorithm of Gratton et al. (1983). Electrode impedance was kept below 10 kΩ. The amplifier bandpass was 0.01–140 Hz. EEG and EOG were sampled continuously with a rate of 2048 Hz. Offline, the EEG was downscaled to a sampling rate of 1000 Hz and cut in stimulus-locked epochs by using the software Vision Analyzer (Brain Products, Munich). Epochs in which the amplitude exceeded ±150 μV were rejected. The ERPs were filtered digitally offline with a 17 Hz low and 0.05 Hz high pass.

DATA ANALYSIS

The first trial of each test block, trials with responses faster than 100 ms or slower than 2500 ms, as well as error trials, were excluded from the RT analysis. Mean RTs, standard deviations of RTs as an index of intraindividual variability of speed (ISDs) and mean error rates were subjected to two ANOVA designs assessing mixing and local effects. The first design included two within-subject factors BLOCK (single, mixed), SESSION (pre-measure: $t1$ vs. post-measure: $t2$) and the between-subject factor GROUP (physical, cognitive, relaxation, control). The second design included the factors TASK SET TRANSITION (non-switch, switch), SESSION ($t1$ vs. $t2$) and the between-subject factor GROUP (physical, cognitive, relaxation, control).

Mixing costs were computed by subtracting mean performance of the single task blocks from the performance in non-switch trials of the mixed block. *Local switch costs* were computed by subtracting non-switch from switch trials of the mixed block.

In case of a significant interaction, a follow-up analysis was conducted. In the next step difference scores ($t2$–$t1$) were computed and a pre-specified *a priori* contrasts were conducted on those differences to determine group effects in training-induced improvements. To this end, we contrasted (1) the control group against the other three groups, (2) the physical and cognitive training groups against the relaxation group, (3) the physical against the cognitive group, (4) the physical against the relaxation group, (5) the cognitive against the relaxation group, (6) the physical against the no-contact group, and (7) the cognitive against the no-contact group. Note the t-values can be either negative or positive depending on a specific difference between the $t2$ and $t1$ scores which are usually negative due to shorter RTs and lower error rates at $t2$ than at $t1$.

The ERP analysis was restricted to the midline electrodes (FCz, Cz, CPz, and Pz) as the N2, P3b, and Ne are usually maximum at these electrodes.

Peak amplitudes and latencies of transient components were measured at their local maximal or minimal amplitudes in pre-defined time windows. In the target-locked ERPs the N2 was measured as the most negative peak at FCz and Cz in the time range 200–400 ms after target onset. The P3b was measured as the most positive peak at CPz and Pz in the time range 300–600 ms after target onset. These post target ERPs were measured relative to 100 ms pre-target baseline. The error negativity (Ne/ERN) and the correct response negativity (Nc/CRN) were measured at FCz in the time range of 0–200 ms after an incorrect resp. correct response relative to 100 ms pre-response interval. The Ne and Nc were analyzed in the mixed block pooled for both types of task set transition (non-switch vs. switch).

The ERP analysis of *mixing effects* included following factors: BLOCK (single, mixed), SESSION ($t1$, $t2$), GROUP (physical, cognitive, relaxation, control), and ELECTRODE. *Local effects* were analyzed by including following factors TASK SET TRANSITION (non-switch, switch), SESSION, GROUP, and ELECTRODE. In each of the omnibus ANOVAs conducted for each ERP parameter we included the factor ELECTRODE and reported the topographical results only when a significant interaction with mixing or local effects occurred. Otherwise, the most negative or positive amplitude of components reached at a particular electrode position, confirmed by a significant effect of ELECTRODE, indicated the site at which the follow-up analysis was conducted. Similarly to the follow-up analysis of behavioral data, we analyzed the above-mentioned pre-defined contrasts.

RESULTS

BEHAVIORAL DATA

Reaction times

Table 2 presents the mean reaction times, error rates, and intraindividual variability expressed in standard deviation for all groups and both sessions. **Figure 2** shows mixing costs (non-switch–single task), and local costs (switch–non-switch) in speed, intraindividual variability of speed and accuracy.

For the analysis of response times, error trials (10.2%) and outliers (5.8%) were discarded.

ANOVA assessing *mixing effects* in mean RTs revealed a main effect of SESSION [$F(1, 137) = 27.5$, $p < 0.001$, $\eta^2 = 0.167$], suggesting faster responses at $t2$ (771 ms) than $t1$ (814 ms) across all groups. There were reliable mixing costs, resulting from a main effect of BLOCK [$F(1, 137) = 574.9$, $p < 0.001$, $\eta^2 = 0.808$] with longer RTs in non-switch trials in the mixed than in the single task block (956 vs. 628 ms). Moreover, SESSION interacted with BLOCK [$F(1, 137) = 17.1$, $p < 0.001$, $\eta^2 = 0.111$], showing reduced mixing costs at $t2$ (300 ms) compared to $t1$ (356 ms). There were no main effect or interactions including the factor GROUP in RTs (all $Fs < 1$). No significant contrasts were found.

Analysis of the intraindividual variability of speed indexed by standard deviations showed a significant effect of SESSION [$F(1, 137) = 22.9$, $p < 0.001$, $\eta^2 = 0.143$], indicating reduced SDs at $t2$ (262 ms) relative to $t1$ (282 ms), an effect of BLOCK [$F(1, 137) = 1376.1$, $p < 0.001$, $\eta^2 = 0.909$], suggesting considerably higher SDs in mixed than single task block (392 vs. 153 ms). Furthermore, there was an interaction SESSION × GROUP [$F(3, 137) = 5.1$, $p < 0.005$, $\eta^2 = 0.102$] as well as a strong trend for

Table 2 | Mean reaction times, error rates and individual standard deviations (with standard deviations in parentheses) for single, non-switch and switch trials for the pre- and postmeasure for each group.

	Physical	Cognitive	Relaxation	Control
REACTION TIMES (ms)				
Pretest				
Single task	642 (88)	622 (81)	639 (96)	637(94)
Non-switch	1025 (264)	984 (210)	1010 (182)	951 (244)
Switch	1205 (310)	1107 (230)	1135 (222)	1058 (285)
Posttest				
Single task	627 (79)	600 (116)	632 (111)	623 (101)
Non-switch	959 (217)	873 (253)	938 (207)	912 (257)
Switch	1071 (276)	964 (283)	1033 (262)	1000 (287)
INDIVIDUAL STANDARD DEVIATIONS (ms)				
Pretest				
Single task	149 (42)	162 (55)	164 (62)	153 (51)
Non-switch	399 (101)	431 (88)	412 (88)	395 (113)
Switch	466 (103)	469 (104)	458 (88)	420 (119)
Posttest				
Single task	149 (35)	142 (59)	158 (56)	148 (50)
Non-switch	394 (87)	348 (101)	385 (75)	371 (101)
Switch	426 (104)	393 (115)	403 (104)	386 (112)
ERROR RATES (%)				
Pretest				
Single task	1.2 (1.4)	2.6 (2.7)	2.5 (2.2)	2.9 (5.7)
Non-switch	18.1 (12.6)	17.4 (14.2)	18.4 (13.1)	13.0 (11.3)
Switch	21.0 (18.5)	19.5 (18.5)	20.7 (14.2)	15.6 (11.8)
Posttest				
Single task	1.2 (1.4)	1.9 (1.7)	2.6 (4.8)	2.5 (3.4)
Non-switch	13.8 (12.1)	8.5 (10.1)	12.6 (10.8)	13.2 (12.8)
Switch	16.8 (17.4)	10.0 (13.7)	14.5 (12.3)	14.7 (15.1)

a SESSION × GROUP × BLOCK interaction [$F(3, 137) = 2.7$, $p = 0.054$, $\eta^2 = 0.054$]. In order to resolve these interactions effects of SESSION and BLOCK were investigated for each group separately. A reliable main effect of SESSION was found in the cognitive group only [$F(1, 31) = 20.1$, $p < 0.001$, $\eta^2 = 0.393$], indicating reduced RT-variability after cognitive training. Moreover, the interaction SESSION × BLOCK [$F(1, 31) = 12.6$, $p < 0.001$, $\eta^2 = 0.290$] suggested that this reduction was mainly due to the mixed (431 vs. 348 ms, $F(1, 31) = 20.8$, $p < 0.001$, $\eta^2 = 0.402$) rather than the single task block [162 vs. 142 ms, $F(1, 31) = 4.2$, $p < 0.05$, $\eta^2 = 0.120$]. No significant reduction of intraindividual variability was found in the remaining groups.

Finally, *a priori* contrasts revealed a reduction of intraindividual variability in speed between $t1$ and $t2$ in the cognitive relative to physical [$t(137) = -2.65$, $p < 0.01$], no-contact [$t(137) = 2.10$, $p < 0.05$] and tendentially relative to the relaxation group [$t(137) = 1.92$, $p = 0.057$].

Regarding *local effects*, ANOVA yielded a main effect of TASK SET TRANSITION [$F(1, 137) = 218.6$, $p < 0.001$, $\eta^2 = 0.615$], reflecting reliable local switch costs in mean RTs (956 vs. 1072 ms, for non-switch and switch trials, respectively) and a main effect of SESSION [$F(1, 137) = 33.0$, $p < 0.001$, $\eta^2 = 0.194$], indicating

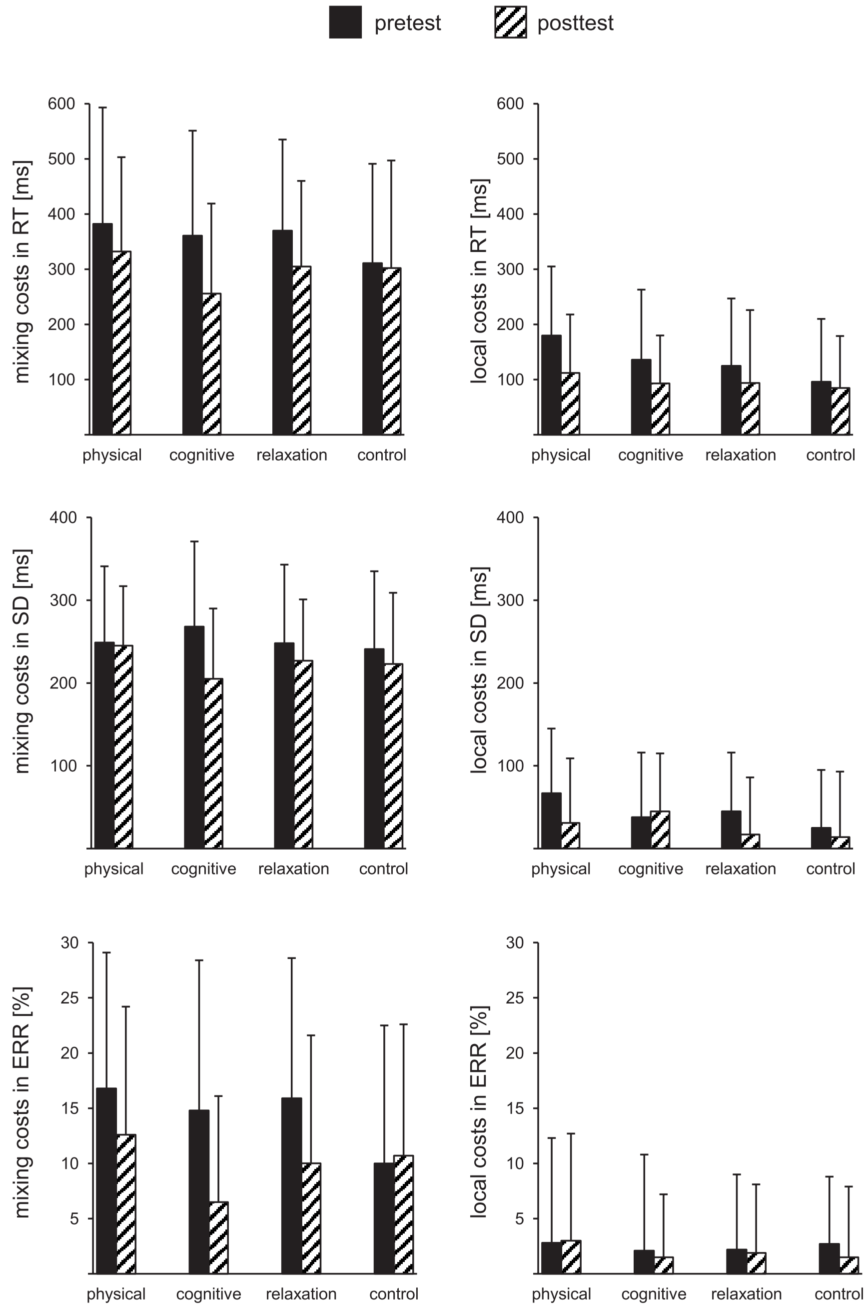

FIGURE 2 | Mixing costs (left) and local costs (right) expressed as the mean reaction times (RT), mean standard deviations (SD), and mean error rates (ERR) for pre- and post-test and each group. The error bars reflect standard deviation.

reduced RTs at $t2$ (969 ms) relative to $t1$ (1059 ms). Moreover, local switch costs were smaller at $t2$ than $t1$ as reflected in an interaction TASK SET TRANSITION × SESSION [$F(1, 137) = 10.4$, $p < 0.005$, $\eta^2 = 0.078$]. However, no main effect of GROUP [$F(1, 137) = 1.3$, $p = 0.33$] nor interactions with GROUP were found.

Analysis of the SDs yielded a main effect of TASK SET TRANSITION [$F(1, 137) = 59.6$, $p < 0.001$, $\eta^2 = 0.303$], suggesting higher variability in task switch than non-switch trials (428 vs. 392 ms) and a main effect of SESSION [$F(1, 137) = 36.9$, $p < 0.001$, $\eta^2 = 0.212$] due to a variability reduction from $t1$ to $t2$ (431 vs. 388 ms). Furthermore, there was a trend for a reduction of local costs in SDs from 44 ms in $t1$ to 27 ms in $t2$ [$F(1, 137) = 3.9$, $p = 0.051$, $\eta^2 = 0.027$]. Finally, there was an interaction SESSION × GROUP [$F(3, 137) = 3.1$, $p < 0.05$, $\eta^2 = 0.062$], indicating a reduction of the SD from $t1$ to $t2$ in the cognitive [450 vs. 370 ms; $F(1, 31) = 21.3$, $p < 0.001$, $\eta^2 = 0.432$], relaxation [435 vs. 394 ms; $F(1, 33) = 8.5$, $p < 0.01$, $\eta^2 = 0.205$], and no-contact [408 vs. 378 ms; $F(1, 39) = 5.8$, $p < 0.05$, $\eta^2 = 0.131$] but not in the physical group [433 vs. 410 ms; $F(1, 34) = 2.7$, $p = 0.10$, $\eta^2 = 0.076$]. However, the planned contrasts revealed no significant local effects, suggesting a similar reduction of intraindividual variability between $t1$ and $t2$ in speed in all groups.

Error rates

Analysis of *mixing effects* in mean error rates yielded a main effect of BLOCK [$F(1, 137) = 182.0$, $p < 0.001$, $\eta^2 = 0.571$] with higher error rates in the mixing (14.4%) than in the single task block (2.2%). The error rates were generally reduced from pre- to post-measure resulting in a main effect of SESSION [$F(1, 137) = 26.4$, $p < 0.001$, $\eta^2 = 0.162$]. BLOCK and SESSION interacted significantly [$F(1, 137) = 21.5$, $p < 0.001$, $\eta^2 = 0.136$], suggesting reduced mixing costs in accuracy at $t2$ (2.0 and 12.0%) relative to $t1$ (2.3 and 16.7%, for single task and non-switch trials, respectively). No main effect of GROUP was found [$F(1, 137) < 1$]. However, significant interactions SESSION × GROUP [$F(3, 137) = 4.1$, $p < 0.01$, $\eta^2 = 0.082$] and BLOCK × SESSION × GROUP [$F(3, 137) = 4.2$, $p < 0.01$, $\eta^2 = 0.084$] were found. To resolve this result pattern the BLOCK × SESSION interaction was analyzed for each group separately. The physical group reduced their errors from $t1$ to $t2$ [9.7 vs. 7.5%; $F(1, 34) = 8.8$, $p < 0.01$, $\eta^2 = 0.205$]. This reduction was larger in the mixed (18.1 vs. 13.8%) than the single task block (1.3 vs. 1.2%), resulting in an interaction of both factors [$F(1, 34) = 8.6$, $p < 0.01$, $\eta^2 = 0.202$]. Similarly, the cognitive training group reduced their errors rates from 10.1% before to 5.2% after the training [$F(1, 31) = 18.9$, $p < 0.001$, $\eta^2 = 0.379$]. This reduction was again larger in the mixed (17.5 vs. 8.5%) than in the single task block (2.6 vs. 2.0%), as shown in an interaction BLOCK × SESSION [$F(1, 31) = 11.9$, $p < 0.005$, $\eta^2 = 0.277$]. The relaxation group also improved accuracy from $t1$ to $t2$ [10.5 vs. 7.6%; $F(1, 33) = 7.1$, $p < 0.05$, $\eta^2 = 0.178$] in mixed (18.4 vs. 12.6%) but not in the single task block (2.5 vs. 2.7%) as indicated by the interaction BLOCK × SESSION [$F(1, 33) = 7.5$, $p < 0.01$, $\eta^2 = 0.186$]. In contrast, no changes from $t1$ to $t2$ were observed in the no-contact group (both Fs < 1).

A priori contrasts showed that the three training groups reduced mixing costs in accuracy more than the no-contact group [$t(137) = 3.25$, $p < 0.001$]. There was also a trend for a reduction of mixing costs after the physical and cognitive trainings relative to the relaxation training [$t(137) = 1.90$, $p = 0.059$] and a clear reduction of mixing costs after cognitive training relative to the no-contact group [$t(137) = 3.35$, $p < 0.001$]. The contrast between the physical and cognitive group did not reach significance [$t(137) = -1.46$, $p = 0.146$].

Regarding *local effects*, ANOVA revealed an effect of TASK SET TRANSITION by higher error rates in task switch than non-switch trials [16.6 vs. 14.4%; $F(1, 137) = 17.9$, $p < 0.001$, $\eta^2 = 0.116$]. These costs did not vary as a function of SESSION or GROUP. A main effect of SESSION [$F(1, 137) = 27.2$, $p < 0.001$, $\eta^2 = 0.165$] indicated lower error rates at $t2$ than $t1$ (13.0 vs. 18.0%). Moreover, SESSION interacted with GROUP [$F(3, 137) = 3.9$, $p < 0.01$, $\eta^2 = 0.079$]. Analyses conducted for each group separately showed effect of SESSION only, i.e., reduction of error rates between $t1$ und $t2$ in the physical [19.5 vs. 15.3%; $F(1, 34) = 5.5$, $p < 0.05$, $\eta^2 = 0.141$], cognitive [18.5 vs. 9.3%; $F(1, 31) = 12.0$, $p < 0.005$, $\eta^2 = 0.279$] and relaxation group [19.5 vs. 13.6%; $F(1, 33) = 10.7$, $p < 0.005$, $\eta^2 = 0.245$], whereas, again no effect was found in the no-contact group ($F < 1$).

The contrasts confirmed the reduction of error rates in the three training groups relative to the no-contact group in non-switch [$t(137) = 3.37$, $p < 0.001$] and switch trials [$t(137) = 2.26$, $p < 0.05$] and a stronger reduction of error rates in the physical and cognitive groups than in the relaxation and no-contact groups for non-switch trials [$t(137) = 2.16$, $p < 0.05$]. Finally, cognitive training group improved the accuracy relative to the no-contact group both in non-switch [$t(137) = 3.69$, $p < 0.001$] and switch trials [$t(137) = 2.70$, $p < 0.01$].

In summary, mixing costs in mean RTs were not differently reduced between the groups from pre to post session. However, intraindividual variability of speed was reliably reduced after cognitive training relative to the other groups. Mixing costs in accuracy were reduced in the three training groups relative to the no-contact group, but the difference to the no-contact group was only significant for the cognitive training group. There were no group specific effects of local costs in reaction times and intraindividual RT-variability. However, the three training groups enhanced the accuracy after training but a reliable improvement relative to the no-contact group was again found for the cognitive training group only.

ERP DATA

Target-locked ERPs are showed in **Figure 3**. In the task implementation phase the N2 and P3b were analyzed. The peak amplitudes of N2 and P3b are depicted in **Figures 4** and **5**.

N2

Mixing effects

The N2 was analyzed as a function of BLOCK (single, mixed), SESSION ($t1$, $t2$), GROUP, and ELECTRODE (FCz, Cz). The ANOVA revealed a main effect of BLOCK [$F(1, 137) = 66.01$, $p < 0.001$, $\eta^2 = 0.325$], suggesting a more pronounced N2 in the single ($-0.8\ \mu V$) than in the non-switch trials of the mixed block ($0.6\ \mu V$) and a main effect of ELECTRODE [$F(1, 137) = 34.24$, $p < 0.001$, $\eta^2 = 0.200$] that was due to a more negative N2 at Cz ($-0.4\ \mu V$) than FCz ($0.2\ \mu V$). No effects or interactions including SESSION or GROUP factors were found.

Local effects

ANOVA yielded a significant main effect ELECTRODE [$F(1, 137) = 20.80$, $p < 0.001$, $\eta^2 = 0.132$] indicating again a more pronounced N2 at Cz ($0.4\ \mu V$) than FCz ($0.9\ \mu V$). Importantly, there was an interaction SESSION × GROUP [$F(1, 137) = 2.98$, $p < 0.05$, $\eta^2 = 0.061$] and SESSION × GROUP × ELECTRODE [$F(1, 137) = 3.87$, $p < 0.01$, $\eta^2 = 0.078$]. In order to resolve this interaction follow-up analyses were conducted for each electrode separately. For FCz no effects or interaction were found. However, at Cz the N2 was more negative at $t2$ ($0.2\ \mu V$) relative to $t1$ ($0.6\ \mu V$) resulting in an effect of SESSION [$F(1, 137) = 4.72$, $p < 0.05$, $\eta^2 = 0.033$). Moreover, SESSION interacted with GROUP [$F(3, 137) = 4.82$, $p < 0.005$, $\eta^2 = 0.096$]. This pattern indicated a more negative N2 in the cognitive group after the training than before [-0.8 vs. $0.3\ \mu V$; $F(1, 31) = 9.18$, $p < 0.005$,

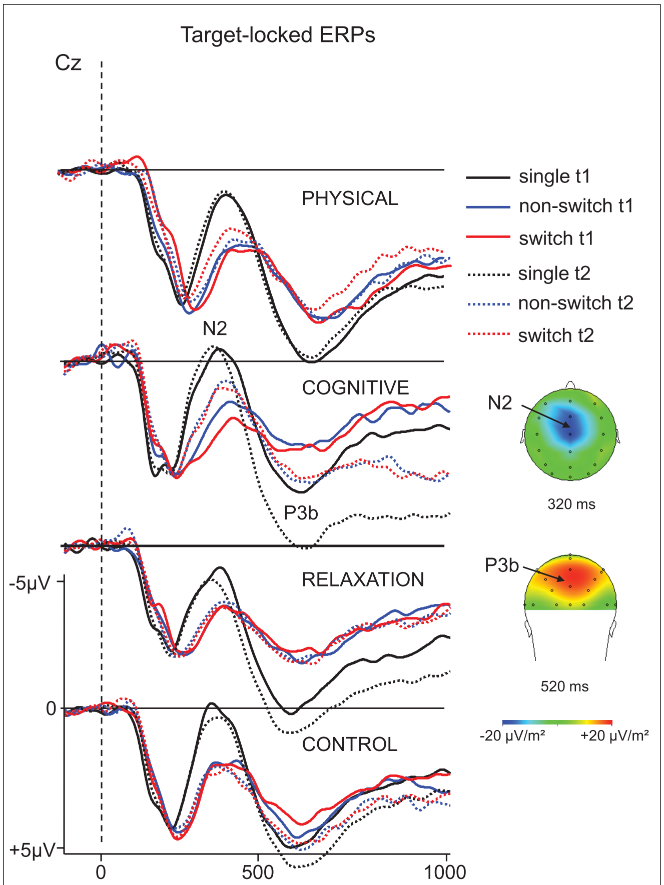

FIGURE 3 | Target-locked ERP – waveforms in correct trials as a function of the three trial types (single task, non-switch and switch trials) and the pre- (*t*1; solid) and post-measure (*t*2; dotted) for each group at electrode Cz. The distribution of the N2 and P3b is visualized in form of topographical maps that illustrate the current densities at 320 ms for the N2 and at 520 ms for the P3b. Dashed line indicates target onset. Negativity is plotted upward.

$\eta^2 = 0.229$] whereas no effect of SESSION was obtained in the other training groups (all $Fs < 1$).The no-contact group even showed a opposite pattern, i.e., a less negative N2 at $t2$ than $t1$ [0.6 vs. 0.1 µV; $F(1, 39) = 5.00$, $p < 0.05$, $\eta^2 = 0.114$]. The N2-effect in the cognitive training group was only tendentially significant in the non-switch trials [0.0 vs. −0.8 µV; $F(1, 31) = 3.55$, $p = 0.06$, $\eta^2 = 0.103$] while there was a highly significant N2 enhancement in the switch trials [0.6 vs. −0.8 µV; $F(1, 31) = 12.59$, $p < 0.001$, $\eta^2 = 0.289$], for $t1$ and $t2$, respectively.

For non-switch trials, the contrasts conducted for the difference $t2$–$t1$ at Cz revealed an N2 increase in all training groups vs. the no-contact group [$t(137) = 1.98$, $p < 0.05$] and an increase of the cognitive vs. the no-contact group [$t(137) = 2.15$, $p < 0.05$]. In task switch trials the contrast between all training groups and the no-contact group was also significant [$t(137) = 3.38$, $p < 0.001$] as well the contrast between the physical and cognitive groups versus the relaxation and no-contact groups [$t(137) = 3.39$, $p < 0.001$] due to higher N2 in the training groups. Finally, the N2 after cognitive training was reliably enhanced relative to the relaxation group [$t(137) = 2.35$, $p < 0.05$] and the no-contact group [$t(137) = 4.02$, $p < 0.001$]. The contrast between physical and cognitive group did not reach significance [$t(137) = -1.59$, $p = 0.11$].

Summarizing, the N2 was substantially increased after cognitive training primarily in task switch trials. Between-group contrasts supported the N2 increase in the cognitive group relative to the relaxation and no-contact groups.

P3b

Mixing effects

For the P3b measured at CPz and Pz the ANOVA showed a main effect of BLOCK [$F(1, 137) = 187.83$, $p < 0.001$, $\eta^2 = 0.578$] which resulted in a substantially larger P3b in the single than mixed block (9.2 vs. 6.3 µV) and an effect of SESSION, indicating higher amplitude at $t2$ vs. $t1$ (8.1 vs. 7.4 µV; $F(1, 137) = 14.44$, $p < 0.001$, $\eta^2 = 0.095$). Moreover, there was an interaction SESSION × GROUP [$F(3, 137) = 2.81$, $p < 0.05$, $\eta^2 = 0.058$] and BLOCK × SESSION × GROUP × ELECTRODE [$F(3, 137) = 2.79$, $p < 0.05$, $\eta^2 = 0.058$]. To resolve this pattern, we analyzed the effect of BLOCK, SESSION and ELECTRODE for each group separately. A main effect of SESSION [$F(1, 31) = 17.18$, $p < 0.001$, $\eta^2 = 0.357$] and an interaction BLOCK × SESSION × ELECTRODE [$F(3, 31) = 7.32$, $p < 0.01$, $\eta^2 = 0.191$] were found for the cognitive group only. Investigating the electrodes separately, the effect of SESSION indicating increased P3b at $t2$ vs. $t1$ was significant at CPz (8.3 vs. 6.7 µV; $F(1, 31) = 15.94$, $p < 0.001$, $\eta^2 = 0.340$ and Pz (8.5 vs. 7.1 µV; $F(1, 31) = 14.32$, $p < 0.001$, $\eta^2 = 0.317$). No interaction SESSION × BLOCK was found. In other words, the P3b was enhanced after the cognitive training both in single task as well as non-switch trials of the mixed task block.

For single task blocks the planned comparisons for the P3b at CPz revealed a larger increase for the cognitive vs. the physical group [$t(137) = 3.05$, $p < 0.005$], and tendentially for the cognitive vs. the relaxation group [$t(137) = -1.96$, $p = 0.052$] and the cognitive vs. the no-contact group [$t(137) = -1.84$, $p = 0.067$].

In the non-switch trials of the mixed block there was an slightly enhanced P3b in the cognitive group, indicated by the trend for the contrast cognitive vs. no-contact group [$t(137) = -1.87$, $p = 0.063$]. This contrast reached significance at Pz [$t(137) = -1.98$, $p < 0.05$]. No further effects were obtained.

LOCAL EFFECTS

The ANOVA investigating the impact of training on the P3b as a function of local effects revealed an effect of SESSION [$F(1, 137) = 6.05$, $p < 0.05$, $\eta^2 = 0.042$] and an interaction SESSION × GROUP × TASK SET TRANSITION × ELECTRODE [$F(3, 137) = 2.77$, $p < 0.05$, $\eta^2 = 0.057$]. To resolve this interaction, we firstly conducted ANOVAs for each electrode separately. At CPz again an effect of SESSION [$F(1, 137) = 6.29$, $p < 0.05$, $\eta^2 = 0.043$] was found, suggesting generally slightly enhanced P3b at $t2$ vs. $t1$ (6.4 vs. 5.9 µV). Moreover, an interaction SESSION × GROUP occurred [$F(3, 137) = 3.77$, $p < 0.05$, $\eta^2 = 0.076$] that implied a different pattern of the P3b in the four groups. At Pz no effects or interactions were found. Thus, in the next step ANOVAs were conducted for each group at CPz: for the physical group an interaction SESSION × TASK SET TRANSITION was significant

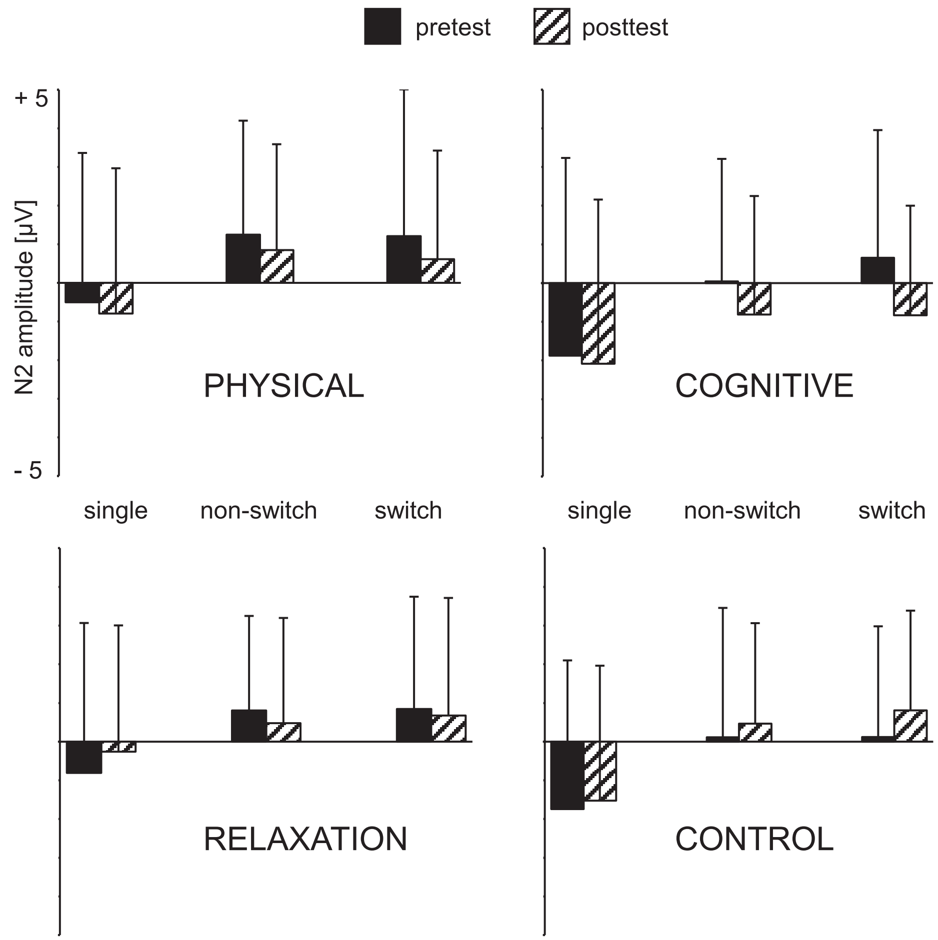

FIGURE 4 | Mean peak amplitudes of the N2 at Cz as a function of the trial type (single task, non-switch and switch trials), session (pre vs. post) and group. The error bars reflect standard deviation (SD).

[$F(1, 34) = 4.57$, $p < 0.05$, $\eta^2 = 0.119$], suggesting a reduction of the P3b in switch trials between $t1$ and $t2$ (7.1 vs. 6.4 µV) and an unchanged amplitude in non-switch trials (6.8 vs. 6.4 µV). For the cognitive group there was a main effect of SESSION [$F(1, 31) = 6.60$, $p < 0.05$, $\eta^2 = 0.176$] indicating a generally increased P3b after training (5.3 vs. 6.5 µV).

The contrasts conducted for switch trials of the mixed block at CPz revealed a P3b enhancement from $t1$ to $t2$ in the physical, cognitive and relaxation groups vs. the no-contact group [$t(137) = -1.97$, $p < 0.05$], a stronger amplitude increase in the cognitive than physical group [$t(137) = 2.64$, $p < 0.01$] and a trend for larger P3b after training in the cognitive than in the relaxation group [$t(137) = -1.74$, $p = 0.078$].

In summary, the P3b was generally enhanced after cognitive training in both single task and mixed blocks. In the physical group a switch specific reduction of the P3b relative to non-switch trials was found after training.

Ne

The response-locked ERPs for the error trials are depicted in **Figure 6**. The peak amplitude of the Ne collapsed across switch and non-switch trials is presented in **Figure 7**.

The analysis of the Ne at FCz for the mixed block revealed a main effect of SESSION [$F(1, 137) = 4.08$, $p < 0.05$, $\eta^2 = 0.029$] and an interaction SESSION × GROUP [$F(3, 137) = 4.45$, $p < 0.005$, $\eta^2 = 0.089$]. In the next step the effect of SESSION was analyzed for each group separately: an increase of the Ne amplitude between $t1$ and $t2$ was found in the cognitive group only [−4.2 vs. −8.1 µV; $F(1, 31) = 8.48$, $p < 0.01$, $\eta^2 = 0.215$].

Planned comparisons between the groups for the $t2$–$t1$ difference showed a substantially higher Ne in the cognitive training group for the contrasts: physical and cognitive vs. relaxation and no-contact group [$t(137) = 2.03$, $p < 0.05$], physical and cognitive vs. relaxation group [$t(137) = -2.27$, $p < 0.05$] and for all individual contrasts between the cognitive group and the other groups: cognitive vs. physical [$t(137) = -2.91$, $p < 0.005$], cognitive vs. relaxation [$t(137) = 2.38$, $p < 0.05$], and cognitive vs. no-contact group [$t(137) = 3.39$, $p < 0.001$].

Nc

The analysis of the negative response-locked potential recorded in correct responses, the Nc measured at FCz revealed no effect of SESSION [$F(1, 137) = 2.85$, $p = 0.09$, $\eta^2 = 0.020$], GROUP and no interaction SESSION × GROUP (both Fs < 1).

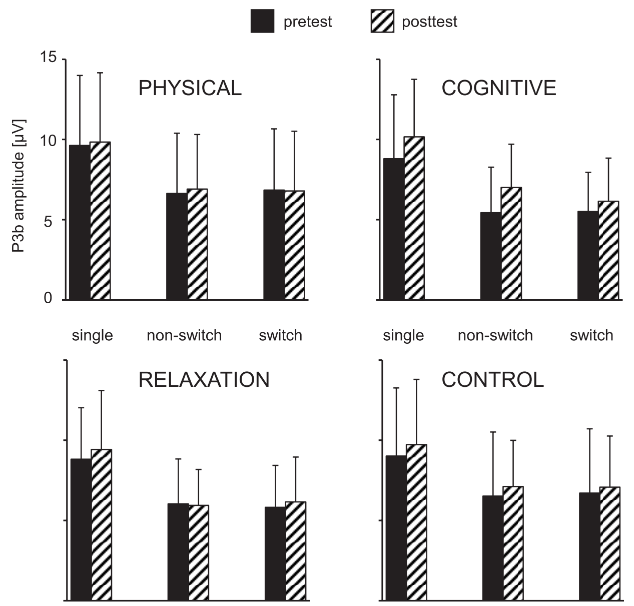

FIGURE 5 | Mean peak amplitudes of the P3b at Pz as a function of the trial type (single task, non-switch and switch trials), session (pre vs. post) and group. The error bars reflect standard deviation (SD).

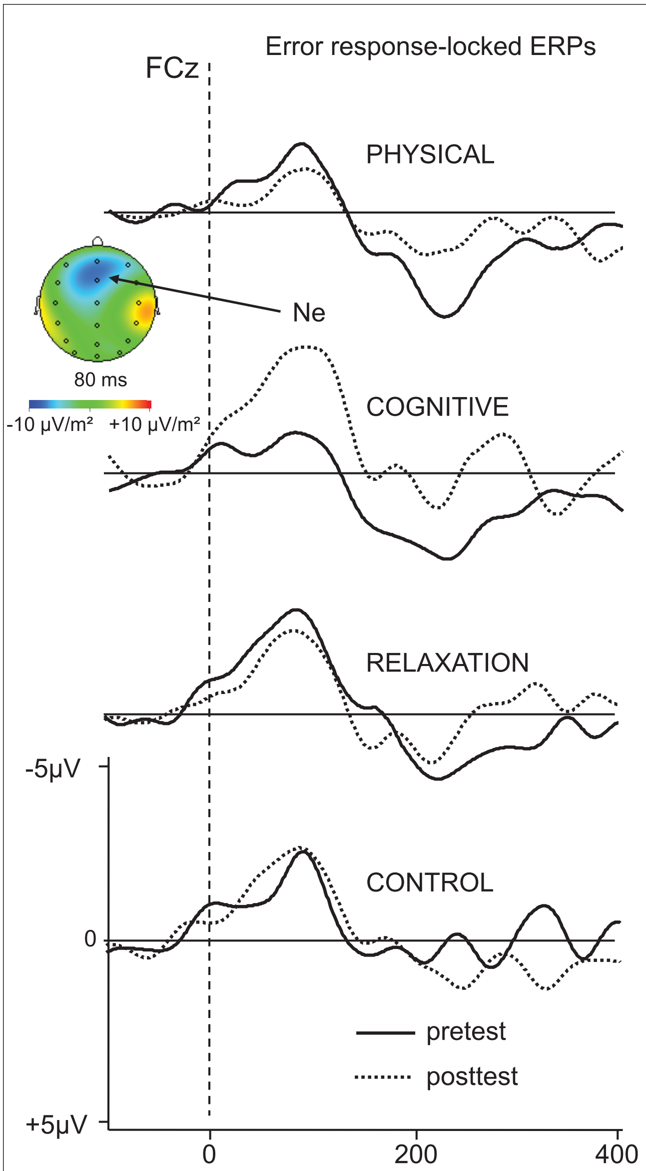

FIGURE 6 | Error-response-locked ERP – waveforms collapsed across non-switch and switch trials as a function of pre- (solid) and post-test (dotted) and participant's group at FCz. Negativity is plotted upward.

In summary, error monitoring indexed by the Ne was strongly enhanced after cognitive training only, whereas no significant changes of the correct response negativity Nc were found.

RELATIONSHIP BETWEEN ERP AND BEHAVIORAL RESULTS

The N2 latency at Cz correlated with RTs in the corresponding conditions at $t1$ in single ($r = 0.33$, $p < 0.001$) and switch trials ($r = 0.27$, $p < 0.001$). The correlations were more consistent at $t2$ (single: $r = 0.43$, $p < 0.001$; non-switch: $r = 0.39$, $p < 0.001$; and switch trials: $r = 0.33$, $p < 0.001$). Moreover, the N2 latency also correlated with error rates at $t1$ in switch trials ($r = 0.25$, $p < 0.005$) and again more consistently at $t2$ (single: $r = 0.16$, $p < 0.05$; non-switch: $r = 0.33$, $p < 0.001$; and switch trials: $r = 0.28$, $p < 0.001$).

The N2 latency vs. RT correlations were absent in the physical group but remained stable in the cognitive group at $t1$ (single: $r = 0.49$, $p < 0.001$; non-switch: $r = 0.35$, $p < 0.05$) and more consistently at $t2$ (single: $r = 0.54$, $p < 0.001$; non-switch: $r = 0.53$, $p < 0.001$; and switch trials: $r = 0.36$, $p < 0.05$). For the relaxation group for switch trials only at $t1$ ($r = 0.57$, $p < 0.001$) and $t2$ ($r = 0.35$, $p < 0.05$) and no-contact group at $t1$ (single: $r = 0.36$, $p < 0.05$; non-switch: $r = 0.47$, $p < 0.005$) and $t2$ (single: $r = 0.47$, $p < 0.005$; non-switch: $r = 0.41$, $p < 0.01$; and switch trials: $r = 0.51$, $p < 0.001$).

No correlations between the N2 amplitude and behavioral data were found.

The Ne amplitude at $t2$ was moderately but significantly correlated with error rates across all groups ($r = 0.20$, $p < 0.05$ and $r = 0.17$, $p < 0.05$) for non-switch and switch trials, respectively. The Ne latency correlated positively with error rates in the switch trials only ($r = 0.20$, $p < 0.05$).

In summary, the N2 latency was consistently correlated with RTs and accuracy in the whole sample. This relationship remained stable primarily for the cognitive and non-contact group. The correlations were enhanced at $t2$ relative to $t1$. The Ne was moderately correlated with error rates in the whole sample.

SUBJECTIVE EVALUATION OF TRAINING

In order to assess the subjective benefit, fun, behavioral changes, and the motivation to continue the training individually, the participants filled in a self-made questionnaire after the training was finished. This also helped to evaluate the training motivation indirectly. For example, regarding the question "Did you like to participate in the training?" 97, 92, and 88% of the participants of

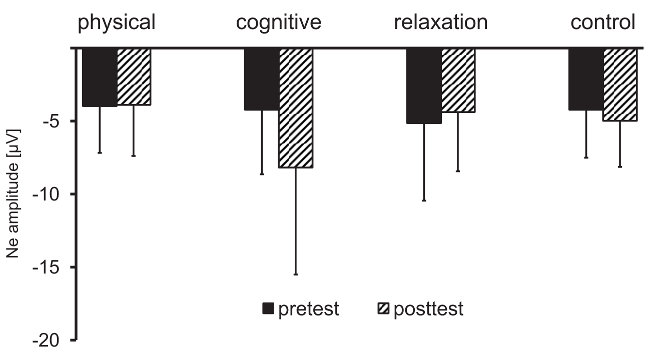

FIGURE 7 | Mean peak amplitude of the error negativity (Ne) collapsed across non-switch and switch trials as a function of session (pre vs. post) and group. The error bars reflect standard deviation (SD).

the physical, cognitive and relaxation group, respectively, answered "Yes." The question "How much did you benefit from training" was answered by 85% of the participants of the physical group "very much" or "much," whereas 79 and 66% of the participants of the cognitive and the relaxation training did so. The question "Do you feel physically better than before the training?": 79, 28, and 43% answered "much" or "very much." The question "Do you feel mentally better than before the training?": 38, 54, and 29% "much" or "very much," for the physical, the cognitive and the relaxation group, respectively. Finally, the question "Do you intend to continue the training after the study is finished?": 73, 56, and 47% answered "Yes," and 21, 40, and 41% "Maybe."

In summary, the subjects subjectively profited from all three interventions; the most fun and subjective benefit was experienced by the participants of the physical training group.

DISCUSSION

The aim of the present study was to investigate neurocognitive changes in aging due to qualitatively different types of training. To this end, 141 participants were randomly assigned to four groups consisting of physical training, cognitive training, relaxation training (contact control), and passive (no-contact control) group. Generally, no group differences were found in mean reaction times neither for mixing nor for local effects. Thus, it appears that different types of training do not affect reaction times in seniors at least in the present study. However, more sensitive behavioral parameters were intraindividual variability of speed and error rates.

In search for differential group effects in mixing costs, the most consistent benefits were found for the cognitive training group. In particular, cognitive training led to a substantial reduction of intraindividual variability of RTs and to a substantial reduction of mixing costs in accuracy. Regarding local effects we found lower RT-Variability in speed after training in all groups but the physical group and reduction of error rates in all groups relative to the no-contact control group. Yet, the strongest decrease of error rates was again found for the cognitive training group as indexed by a reliable contrast between this group and the no-contact group.

The electrophysiological markers should help to differentiate between sub-processes that were susceptible to training. Indeed, the mixing and local improvements in performance were associated with changes in event-related potentials. Overall, N2, P3b, and Ne were found to be enhanced after the cognitive training.

Firstly, during task implementation the identified target stimulus has to be associated with a particular task rule that enables selection of a response. In this phase an enhancement of the frontocentral N2 after cognitive training in the mixing task block was found. This enhancement in the stimulus-locked averages is not likely a simple reflection of the enhancement of the Ne in the response-locked averages (see below), because the N2 was measured in correct trials only, while the Ne was measured in the error trials, and no difference was found for the Nc in the response-locked correct trials. Our previous studies suggest that N2 reflects the process of response selection which is delayed by conflict or task set interference (Gajewski et al., 2008, 2010a, 2011). In other words, the N2 appears to reflect a decision process, as already proposed decades ago (Ritter et al., 1979, 1982; Towey et al., 1980). Therefore, the increased N2 after cognitive training suggests an improvement of response selection in general and hence, lower error rates and less speed variability after the training. This was supported by positive correlations between N2 latency and RTs and Ne amplitude and error rates, particularly after the training. As the N2 increase after cognitive training was related to a decrease of intraindividual variability of speed, it is plausible to assume that the lower the variability of the response selection process the lower the variability in RTs. Thus, the training-induced N2 increase in the average ERP may not only occur due to an elevation of the N2 amplitude, but also in consequence of a better synchronization of the N2 with the target and response in every trial, which should result in a larger component in the average ERP.

Secondly, the P3b was substantially enhanced both in the single and mixing blocks in the cognitive training group, suggesting generally higher available cognitive resources to perform the task (Kok, 2001), which may also be interpreted as enhanced neuronal integrity supported by reduced intraindividual variability of RTs.

Regarding local effects, the physical training led to a reduction of the P3b in switch relative to non-switch trials. This P3b pattern is usually observed in young subjects during switching tasks (e.g., Barceló et al., 2000; Lorist et al., 2000; Rushworth et al., 2002) that is mainly due to an increased N2 in the switch trials (Gajewski and Falkenstein, 2011b). However, this pattern was not observed before the training in the physical training group. The emergence of this pattern may correspond to the reduction of behavioral local switch costs after training (see **Figures 2** and **3**), which were particularly high at the pre-measure in this group. This suggests that the cognitive training generally enhanced the processing resources, resulting in lower global costs, while physical training specifically improved the switch process, resulting in lower local costs.

Finally, a highly consistent change was observed for the error negativity (Ne; Falkenstein et al., 1991), which was substantially increased after cognitive training only. We assume that the increase of the Ne is mainly a consequence of the improvement of response selection, as reflected in the enhanced N2. This implies that the enhanced cognitive resources indexed by the P3b led to a more efficient activation of stimulus–response associations in terms of response selection reflecting in the N2 and higher awareness about the required response, as reflected in an enhanced Ne.

In sum, the results of the present study suggest that a multilayered formal cognitive training consisting of paper and pencil- and PC-based trainings led to an improvement of response selection processing capacity and error detection, which have not been demonstrated in previous studies.

One principal criticism of cognitive trainings is a rather limited transfer of brain training upon other non-trained functions or let alone daily life activities. Near transfer and far transfer to other cognitive functions has been reported when task switching was trained (Minear and Shah, 2008; Karbach and Kray, 2009). The present study also demonstrates a far transfer on mixing and local effects in accuracy, RT-variability, and ERPs, though our participants did not train task switching *per se* or other executive tasks but rather a broad range of basic functions like visual attention, short-term memory, speed of processing, visuospatial processing, and vigilance. Hence, the improvements in maintaining and coordinating task sets and selective reduction of error rates we found for the cognitive training group indicate some far transfer to not explicitly trained functions. However, it is quite possible that the improvement of performance after cognitive training is not restricted to the task switching situation. On the contrary, it is indeed plausible to assume that the improved response selection, processing capacity and error monitoring enhance performance in a number of other tasks. This should be tested in future training studies.

Existing literature showed repeatedly benefits of physical training on cognitive functions (e.g., Colcombe and Kramer, 2003). In the present study the physical training group decreased mixing and local costs in errors but this reduction was smaller than in the cognitive training group. We assume that the relatively short training duration of 4 months and frequency of two times per week with 90 min per session, was probably not sufficient to obtain strong training effects (c.f. Kramer and Erickson, 2007). This suggests that cognitive and physical training have different time ranges of efficiency, and future training studies should take this into account.

Finally, with regard to the relaxation training we included this group to control a confounding factor like new activity in a social context. To our knowledge, the prevailing literature reports no effect of relaxation training on cognitive functions in seniors. Of course, there is a strong connection between affective and cognitive functions as affective disorders or chronic stress impair cognitive functions like memory (McEwen, 2007). Thus, reduction of stress due to relaxation training may improve cognitive functions. However, as our participants dropped out from working life, no substantial level of stress was expected which may be diminished in course of the training. Nevertheless, similar to the physical and cognitive training groups, participants of the relaxation group reduced error rates relative to the no-contact group but again only if this group was tested together with the other training groups against the no-contact group. However, simple contrasts against the no-contact group did not reveal any reliable differences. The origin of this moderate effect cannot be unequivocally localized: it could be either due to the training intervention or was a by-product of a new experience in a social group. At least, we can clearly exclude the possibility that the improvement was induced by repeated measurements as no such benefit was found in the passive control group. Despite this effect, the participants of the relaxation group did not improve their performance to the extent of the cognitive training group.

There are some limitations of the study that deserve consideration. Firstly, the sample of the present study was selected from about 467 volunteers aged about 65. The selection criteria like a good physical and mental constitution but no regular physical or mental activity in a sport club or association implies a discrepancy and induced a selection of relatively fit seniors. Therefore, our study is not representative for the average population but merely for a subpopulation of relatively fit persons, regardless of other sociodemographic variables. Since training effects are most likely larger for people with lower cognitive and physical status, we probably underestimated the training effects in the entire population. In future studies seniors with lower cognitive and physical status should be trained.

Secondly, as all trainings consisted of a number of sub-trainings and exercises, the crucial components that may lead to the specific improvement of performance remain unclear. Moreover, it is well possible that the three trainings differed in regard to other components, such as attractivity which may have affected training motivation. We aimed at creating varying and multilayered trainings in order to avoid monotony and to enhance the motivation for all three active groups but the motivation was not directly measured. Nevertheless, a post-training questionnaire provides some information regarding the subjective benefits, fun and the behavioral changes due to the training and the motivation to continue the training individually. By tendency, the physical group experienced qualitatively the most fun and subjective benefits, followed by the cognitive and relaxation group. This argues against motivation as crucial factor for the high benefits in the cognitive group.

Finally, the reason for the improvements in accuracy and variability of speed but not in the mean reaction times may be due to a particular difficult experimental paradigm including three tasks. The error rates were considerably high at pre-measure, which allowed enough space for improvement. More extensive pre-experimental practice would reduce *a priori* error rates and possibly reveal effects on reaction times as showed in other studies (e.g., Karbach and Kray, 2009).

Taken together, results of the present study agree with findings obtained in other cognitive training studies with young (Klingberg et al., 2005; Jaeggi et al., 2008, 2011; Karbach and Kray, 2009) and older adults (Willis and Schaie, 1986; Willis et al., 2006; Bielak et al., 2007; Buschkuehl et al., 2008; Li et al., 2008; Dahlin et al., 2009; Klusmann et al., 2010). We found clear improvements particularly in accuracy and intraindividual speed variability due to formal cognitive training and could specify the loci of the training effects with ERPs. Moreover, our study provides evidence for some qualitative differences of the effects of physical and cognitive training, which were also supported by electrophysiological measures. This suggests a promising application of a combined training that may enhance a large scale of cognitive processing in older people and hence increase the chance of transfer to daily activities.

CONCLUSION

The most consistent behavioral and neuronal changes in our training study occurred in the cognitive training group, which showed improvements in maintaining and coordinating multiple task sets indexed by reduced costs in accuracy and lower RT-variability. This finding was supported by an increased frontocentral N2, suggesting improved and/or more synchronized response selection and an enhanced P3b, indicating a better allocation of cognitive resources and higher processing capacity. Finally, the considerable reduction of error rates in the mixed block was associated with enhanced error detection indexed by an increased Ne, which may be a consequence of the improved response selection. These results indicate that the behavioral improvements are mainly due to improvements in response selection which also leads to better error detection.

These findings suggest neurocognitive plasticity of aging brains which can be stimulated not only by aerobic training but also by broad and multilayered paper and pencil and PC-based cognitive training, which also transfers to not directly trained functions. To our knowledge, this is the first study that demonstrates effects of cognitive training with ERP measures.

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REFERENCES

Allport, A., Styles, E. A., and Hsieh, S. (1994). "Shifting intentional set: exploring the dynamic control of tasks," in *Attention and Performance XV*, eds C. Umiltà and M. Moscovitch (Cambridge, MA: MIT Press), 421–452.

Ball, K., Berch, D. B., Helmers, K. F., Jobe, J. B., Leveck, M. D., Marsiske, M., Morris, J. N., Rebok, G. W., Smith, D. M., Tennstedt, S. L., Unverzagt, F. W., and Willis, S. L. (2002). Effects of cognitive training interventions with older adults – a randomized controlled trial. *JAMA* 288, 2271–2281.

Ball, K., Edwards, J. D., and Ross, L. A. (2007). The impact of speed of processing training on cognitive and everyday functions. *J. Gerontol. B Psychol. Sci. Soc. Sci.* 62, 19–31.

Baltes, P. B., and Lindenberger, U. (1997). Emergence of a powerful connection between sensory and cognitive functions across the adult life span: a new window to the study of cognitive aging? *Psychol. Aging* 12, 12–21.

Band, G. P. H., and Kok, A. (2000). Age effects on response monitoring in a mental rotation task. *Biol. Psychol.* 51, 201–221.

Barceló, F., Muñoz-Céspedes, J. M., Pozo, M. A., and Rubia, F. J. (2000). Attentional set shifting modulates the target P3b response in the Wisconsin card sorting test. *Neuropsychologia* 38, 1342–1355.

Basak, C., Boot, W. R., Voss, M. W., and Kramer, A. F. (2008). Can training in a real-time strategy video game attenuate cognitive decline in older adults? *Psychol. Aging* 23, 765–777.

Becic, E., Boot, W. R., and Kramer, A. F. (2008). Training older adults to search more effectively: scanning strategy and visual search in dynamic displays. *Psychol. Aging* 23, 461–466.

Beck, A. T., Ward, C. H., Mendelson, M., Mock, J., and Erbaugh, J. (1961). An inventory for measuring depression. *Arch. Gen. Psychiatry* 4, 561–571.

Bherer, L., Kramer, A. F., Peterson, J. S., Colcombe, S., Erickson, K., and Becic, E. (2005). Training effects on dual-task performance: are there age-related differences in plasticity of attentional control? *Psychol. Aging* 20, 695–709.

Bielak, A. A., Hughes, T. F., Small, B. J., and Dixon, R. A. (2007). It's never too late to engage in lifestyle activities: significant concurrent but not change relationships between lifestyle activities and cognitive speed. *J. Gerontol. B Psychol. Sci. Soc. Sci.* 62, 331–339.

Buschkuehl, M., Jaeggi, S. M., Hutchison, S., Perrig-Chiello, P., Däpp, C., Müller, M., Breil, F., Hoppeler, H., and Perrig, W. J. (2008). Impact of working memory training on memory performance in old-old adults. *Psychol. Aging* 23 , 743–753.

Caserta, R. J., Young, J., and Janelle, C. M. (2007). Old dogs, new tricks: training the perceptual skills of senior tennis players. *J. Sport Exerc. Psychol.* 29, 479–497.

Cassavaugh, N., and Kramer, A. F. (2009). Transfer of computer-based cognitive training to simulated driving in older adults. *Appl. Ergon.* 40, 943–952.

Cepeda, N. J., Kramer, A. F., and Gonzalez de Sather, J. C. (2001). Changes in executive control across the life span: examination of task-switching performance. *Dev. Psychol.* 37, 715–730.

Colcombe, S., and Kramer, A. F. (2003). Fitness effects on the cognitive function of older adults: a meta-analytic study. *Psychol. Sci.* 14, 125–130.

Colcombe, S. J., Kramer, A. F., Erickson, K. I., Scalf, P., McAuley, E., Cohen, N. J., Webb, A., Jerome, G. J., Marquez, D. X., and Elavsky, S. (2004). Cardiovascular fitness, cortical plasticity, and aging. *Proc. Natl. Acad. Sci. U.S.A.* 101, 3316–3321.

Costa, P. T. Jr., and McCrae, R. R. (1992). *Revised NEO Personality Inventory (NEO-PI-R) and NEO Five-Factor Inventory (NEO-FFI) Professional Manual.* Odessa: Psychological Assesment Ressources, Inc.

Craik, F. I. M., and Salthouse, T. A. (eds). (2000) *The Handbook of Aging and Cognition*, 2nd Edn. Mahwah, NJ: Erlbaum.

Dahlin, E., Bäckman, L., Neely, A. S., and Nyberg, L. (2009). Training of the executive component of working memory: subcortical areas mediate transfer effects. *Restor. Neurol. Neurosci.* 27, 405–419.

De Jong, R. (2001). Adult age differences in goal activation and goal maintenance. *Eur. J. Cogn. Psychol.* 13, 71–89.

Donchin, E. (1981). Surprise!... Surprise? *Psychophysiology* 18, 493–513.

Donchin, E., and Coles, M. G. H. (1988). Is the P300 component a manifestation of context updating? *Behav. Brain Sci.* 11, 357–374.

Düzel, E., Bunzeck, N., Guitart-Masip, M., and Düzel, S. (2010). Novelty-related motivation of anticipation and exploration by dopamine (NOMAD): implications for healthy aging. *Neurosci. Biobehav. Rev.* 34, 660–669.

Edwards, J. D., Myers, C., Ross, L. A., Roenker, D. L., Cissell, G. M., McLaughlin, A. M., and Ball, K. K. (2009). The longitudinal impact of cognitive speed of processing training on driving mobility. *Gerontologist* 49, 485–494.

Erickson, K. I., Voss, M. W., Prakash, R. S., Basak, C., Szabo, A., Chaddock, L., Kim, J. S., Heo, S., Alves, H., White, S. M., Wojcicki, T. R., Mailey, E., Vieira, V. J., Martin, S. A., Pence, B. D., Woods, J. A., McAuley, E., and Kramer, A. F. (2011). Exercise training increases size of hippocampus and improves memory. *Proc. Natl. Acad. Sci. U.S.A.* 108, 3017–3022.

Falkenstein, M., Hohnsbein, J., and Hoormann, J. (1991). Effects of crossmodal divided attention on late ERP components. II. Error processing in choice reaction tasks. *Electroencephalogr. Clin. Neurophysiol.* 78, 447–455.

Falkenstein, M., Hoormann, J., Christ, S., and Hohnsbein, J. (2000). ERP components on reaction errors and their functional significance: a tutorial. *Biol. Psychol.* 51, 87–107.

Falkenstein, M., Hoormann, J., and Hohnsbein, J. (2001). Changes of error-related ERPs with age. *Exp. Brain Res.* 138, 258–262.

Falkenstein, M., Hoormann, J., and Hohnsbein, J. (2002). Inhibition-related ERP components: variation with age and time-on-task. *J. Psychophysiol.* 16, 167–175.

Folstein, M. F., Folstein, S. E., and McHugh, P. R. (1975). Mini-mental state. A practical method for grading the cognitive state of patients for the clinican. *J. Psychiatr. Res.* 12, 189–198.

Frick, K. M., and Fernandez, S. M. (2003). Enrichment enhances spatial memory and increases synaptophysin levels in aged female mice. *Neurobiol. Aging* 24, 615–626.

Gajewski, P. D., and Falkenstein, M. (2011a). Neurocognition of aging in working einvironments. *J. Labour Market Res.* 44, 307–320.

Gajewski, P. D., and Falkenstein, M. (2011b). Diversity of the P3 in the task-switching paradigm. *Brain Res.* 1411, 87–97.

Gajewski, P. D., Hengstler, J., Golka, K., Falkenstein, M., and Beste C. (2011). The Met-allele of the BDNF Val66Met polymorphism enhances task switching in elderly. *Neurobiol. Aging* 32, 2327.e7–2327.e19.

Gajewski, P. D., Kleinsorge, T., and Falkenstein, M. (2010a). Electrophysiological correlates of residual switch costs. *Cortex* 46 , 1138–1148.

Gajewski, P. D., Wild-Wall, N., Schapkin, S. A., Erdmann, U., Freude, U., and Falkenstein, M. (2010b). Effects of aging and job demands on cognitive flexibility assessed by task switching. *Biol. Psychol.* 85, 187–199.

Gajewski, P. D., Stoerig, P., and Falkenstein, M. (2008). ERP – correlates of response selection in a response conflict paradigm. *Brain Res.* 1189, 127–134.

Gehring, W. J., Goss, B., Coles, M. G., and Meyer, D. E. (1993). A neural system for error detection and compensation. *Psychol. Sci.* 4, 385–390.

Gopher, D., Weil, M., and Bareket, T. (1994). Transfer of skill from a computer game trainer to flight. *Hum. Factors* 36, 387–405.

Gratton, G., Coles, M. G. H., and Donchin, E. (1983). A new method for off-line removal of ocular artifact. *Electroencephalogr. Clin. Neurophysiol.* 55, 468–484.

Green, C., and Bavelier, D. (2003). Action video game modifies visual selective attention. *Nature* 423, 534–537.

Greenwood, P. M. (2007). Functional plasticity in cognitive aging: review and hypothesis. *Neuropsychology* 21, 657–673.

Greenwood, P. M., and Parasuraman, R. (2010). Neuronal and cognitive plasticity: a neurocognitive framework for ameliorating cognitive aging. *Front. Aging Neurosci.* 2:150. doi:10.3389/fnagi. 2010.00150

Hertzog, C., Kramer, A. F., Wilson, R. S., and Lindenberger, U. (2008). Enrichment effects on 656 adult cognitive development. *Psychol. Sci. Public Interest* 9, 1.

Hertzog, C., Kramer, A. F., Wilson, R. S., and Lindenberger, U. (2009). Enrichment effects on adult cognitive development: can the functional capacity of older adults be preserved and enhanced? *Psychol. Sci. Public Interest* 9, 1–65.

Heyn, P., Abreu, B. C., and Ottenbacher, K. J. (2004). The effects of exercise training on elderly persons with cognitive impairment and dementia: a meta-analysis. *Arch. Phys. Med. Rehabil.* 85, 1694–1704.

Hillman, C. H., Erickson, K. I., and Kramer, A. F. (2008). Be smart, exercise your heart: exercise effects on brain and cognition. *Nat. Rev. Neurosci.* 9, 58–65.

Hultsch, D. F., Hertzog, C., Small, B. J., and Dixon, R. A. (1999). Use it or lose it: engaged lifestyle as a buffer of cognitive decline in aging? *Psychol. Aging* 14, 245–263.

Hultsch, D. F., and MacDonald, S. W. S. (2004). "Intraindividual variability in performance as a theoretical window onto cognitive aging," in *New Frontiers in Cognitive Aging*, eds R. A. Dixon, L. Backman, and L.-G. Nilsson (Oxford: Oxford University Press), 65–88.

Ilg, R., Wohlschlager, A. M., Gaser, C., Liebau, Y., Dauner, R., Woller, A., and Zimmer C, Zihl J, Mühlau M. (2008). Gray matter increase induced by practice correlates with task-specific activation: a combined functional and morphometric magnetic resonance imaging study. *J. Neurosci.* 28, 4210–4215.

Jaeggi, S. M., Buschkuehl, M., Jonides, J., and Perrig, W. J. (2008). Improving fluid intelligence with training on working memory. *Proc. Natl. Acad. Sci. U.S.A.* 105, 6829–6833.

Jaeggi, S. M., Buschkuehl, M., Jonides, J., and Shah, P. (2011). Short- and long-term benefits of cognitive training. *Proc. Natl. Acad. Sci. U.S.A.* 108, 10081–10086.

Jasper, H. H. (1958). The 10–20 electrode system of the International Federation. *Electroencephalogr. Clin. Neurophysiol.* 10, 370–375.

Jones, S., Nyberg, L., Sandblom, J., Stigsdotter Neely, A., Ingvar, M., Magnus Petersson, K., and Bäckman L. (2006). Cognitive and neural plasticity in aging: general and task-specific limitations. *Neurosci. Biobehav. Rev.* 30, 864–871.

Karbach, J., and Kray, J. (2009). How useful is executive control training? Age differences in near and far transfer of task-switching training. *Dev. Sci.* 12, 978–990.

Kempermann, G., Kuhn, H. G., and Gage, F. H. (1997). More hippocampal neurons in adult mice living in an enriched environment. *Nature* 386, 493–495.

Kiesel, A., Steinhauser, M., Wendt, M., Falkenstein, M., Jost, K., Phillip, A., and Koch, I. (2010). Control and interference in task switching – a review. *Psychol. Bull.* 136, 849–874.

Klingberg, T., Fernell, E., Olesen, P., Johnson, M., Gustafsson, P., and Dahlstrom, K Gillberg CG, Forssberg H, Westerberg H. (2005). Computerized training of working memory in children with ADHD – a randomized, controlled trial. *J. Am. Acad. Child Adolesc. Psychiatry* 44, 177–186.

Klingberg, T., Forssberg, H., and Westerberg, H. (2002). Training of working memory in children with ADHD. *J. Clin. Exp. Neuropsychol.* 24, 781–791.

Klusmann, V., Evers, A., Schwarzer, R., Schlattmann P., Reischies, F. M., Heuser, I., and Dimeo, F. C. (2010). Complex mental and physical activity in older women and cognitive performance: a 6-month randomized controlled trial. *J. Gerontol. A Biol. Sci. Med. Sci.* 65, 680–688.

Kok, A. (2001). On the utility of P3 amplitude as a measure of processing capacity. *Psychophysiology* 38, 557–577.

Kolev, V., Falkenstein, M., and Yordanova, J. (2005). Aging and error processing. Time-frequency analysis of error-related potentials. *J. Psychophysiol.* 19, 289–297.

Kramer, A. F., and Erickson, K. I. (2007). Effects of physical activity on cognition, well-being and brain: human interventions. *Alzheimers Dement.* 3, 45–51.

Kramer, A. F., Erickson, K. I., and Colcombe, S. J. (2006). Exercise, cognition, and the aging brain. *J. Appl. Physiol.* 101, 1243–1251.

Kramer, A. F., Hahn, S., and Gopher, D. (1999). Task coordination and aging: explorations of executive control processes in the task switching paradigm. *Acta Psychol.* 101, 339–378.

Kramer, A. F., and Morrow, D. (in press). "Cognitive training and expertise," in *Cognitive Aging: A Primer*, eds D. Park and N. Schwartz (Philadelphia: Psychology Press).

Kray, J. (2006). Task-set switching under cue-based versus memory-based switching conditions in younger and older adults. *Brain Res.* 1105, 83–92.

Kray, J., Eber, J., and Lindenberger, U. (2004). Age differences in executive functioning across the lifespan: the role of verbalization in task preparation. *Acta Psychol.* 115,143–165.

Kray, J., and Lindenberger, U. (2000). Adult age differences in task switching. *Psychol. Aging* 15, 126–147.

Lehrl, S., Lehrl, M., and Weickmann, E. (1994). *MAT Gehirnjogging, Einführung in das MentaleAktivierungsTraining.* Ebersberg: Vless Verlag.

Lehrl, S., Triebig, G., and Fischer, B. (1995). Multiple choice vocabulary test MWT as a valid and short test to estimate premorbid intelligence. *Acta Neurol. Scand.* 91, 335–345.

Li, S. C., Schmiedek, F., Huxhold, O., Röcke, C., Smith, J., and Lindenberger, U. (2008). Working memory plasticity in old age: practice gain, transfer, and maintenance. *Psychol. Aging* 23 , 731–742.

Lindenberger, U., Nagel, I. E., Chicherio, C., Li, S., Heekeren, H. R., and Bäckman, L. (2008). Age-related decline in brain resources modulates genetic effects on cognitive functioning. *Front. Neurosci.* 2:2. doi:10.3389/neuro.01.039.2008

Liu-Ambrose, T., Nagamatsu, L. S., Graf, P., Beattie, B. L., Ashe, M. C., and Handy, T. C. (2010). Resistance training and executive functions: a 12-month randomized controlled trial. *Arch. Intern. Med.* 170, 170–178.

Lorist, M. M., Klein, M., Nieuwenhuis, S., De Jong, R., Mulder, G., and Meijman, T. F. (2000). Mental fatigue and task control: planning and preparation. *Psychophysiology* 37, 614–625.

Lustig, C., Shah, P., Seidler, R., and Reuter-Lorenz, P. A. (2009). Aging, training, and the brain: a review and future directions. *Neuropsychol. Rev.* 19, 504–522.

Mayr, U. (2001). Age differences in the selection of mental sets: the role of inhibition, stimulus ambiguity, and response-set overlap. *Psychol. Aging* 16, 96–109.

Mayr, U., and Liebscher, T. (2001). Is there an age deficit in the selection of mental sets? *Eur. J. Cogn. Psychol.* 13, 47–69.

McAuley, E., Kramer, A. F., and Colcombe, S. J. (2004). Cardiovascular fitness and neurocognitive function in older adults: a brief review. *Brain Behav. Immun.* 18, 214–220.

McEwen, B. S. (2007). Physiology and neurobiology of stress and adaptation: central role of the brain. *Physiol. Rev.* 87, 873–904.

Meiran, N. (1996). Reconfiguration of processing mode prior to task performance. *J. Exp. Psychol. Learn. Mem. Cogn.* 22, 1423–1442.

Meiran, N., Gotler, A., and Perlman, A. (2001). Old age is associated with a pattern of relatively intact and relatively impaired task-set switching abilities. *J. Gerontol. B Psychol. Sci. Soc. Sci.* 56, 88–102.

Milgram, N., Siwak-Tapp, C., Araujo, J., and Head, E. (2006). Neuroprotective effects of cognitive enrichment. *Ageing Res. Rev.* 5, 354–369.

Minear, M., and Shah, P. (2008). Training and transfer effects in task switching. *Mem. Cognit.* 36, 1470–1483.

Mozolic, J. L., Hayasaka, S., and Laurienti, P. J. (2010). A cognitive training intervention increases resting cerebral blood flow in healthy older adults. *Front. Hum. Neurosci.* 4:16. doi:10.3389/neuro.09.016.2010

Pereira, A. C., Huddleston, D. E., Brickman, A. M., Sosunov, A. A., Hen, R., McKhann, G. M., Sloan, R., Gage, F. H., Brown, T. R., and Small, S. A. (2007). An in vivo correlate of exercise-induced neurogenesis in the adult dentate gyrus. *Proc. Natl. Acad. Sci. U.S.A.* 104, 5638–5643.

Polich, J. (2007). Updating P300: an integrative theory of P3a and P3b. *Clin. Neurophysiol.* 118,128–148.

Ram, N., Stollery, B., Rabbit, P., and Nesselroade, J. R. (2005). Cognitive performance inconsistency: intraindividual change and variability. *Psychol. Aging* 20, 623–633.

Reinke, K. S., He, Y., Wang, C., and Alain, C. (2003). Perceptual learning modulates sensory evoked response during vowel segregation. *Brain Res.* 17, 781–791.

Ritter, W., Simson, R., and Vaughan, H. G. Jr. (1983). Event-related potential correlates of two stages of information processing in physical and semantic discrimination tasks. *Psychophysiology* 20, 168–179.

Ritter, W., Simson, R., Vaughan, H. G. Jr., and Friedman, D. (1979). A brain event related to the making of a sensory discrimination. *Science* 203, 1358–1361.

Ritter, W., Simson, R., Vaughan, H. G. Jr„ and Macht M. (1982). Manipulation of event-related potential manifestations of information processing stages. *Science* 218, 909–911.

Roche, R. A., and O'Mara, S. M. (2003). Behavioural and electrophysiological correlates of visuomotor learning during a visual search task. *Brain Res.* 15, 127–136.

Rogers, R. D., and Monsell, S. (1995). Costs of a predictable switch between simple cognitive tasks. *J. Exp. Psychol. Gen.* 124, 207–231.

Rushworth, M. F., Passingham, R. E., and Nobre, A. C. (2002). Components of switching intentional set. *J. Cogn. Neurosci.* 14, 1139–1150.

Salthouse, T. A. (2009). When does age-related cognitive decline begin? *Neurobiol. Aging* 30, 507–514.

Singh-Manoux, A., Richards, M., and Marmot, M. (2003). Leisure activities and cognitive function in middle age: evidence from the Whitehall II study. *J. Epidemiol. Community* 57, 907–913.

Smiley-Oyen, A. L., Lowry, K. A., Francois, S. J., Kohut, M. L., and Ekkekakis, P. (2008). Exercise, fitness, and neurocognitive function in older adults: the "selective improvement" and "cardiovascular fitness" hypothesis. *Ann. Behav. Med.* 36, 280–291.

Song, Y., Ding, Y., Fan, S., Qu, Z., Xu, L., Lu, C., and Peng D. (2005). Neural substrates of visual perceptual learning of simple and complex stimuli. *Clin. Neurophysiol.* 116, 632–639.

Swaab, D. F., and Bao, A. M. (2011). (Re-)activation of neurons in aging and dementia: lessons from the hypothalamus. *Exp. Gerontol.* 46, 178–184.

Takeuchi, H., Sekiguchi, A., Taki, Y., Yokoyama, S., Yomogida, Y., Komuro, N., and Yamanouchi T, Suzuki S, Kawashima R. (2010). Training of working memory impacts structural connectivity. *J. Neurosci.* 30, 3297–3303.

Tong, Y., Melara, R. D., and Rao, A. (2009). P2 enhancement from auditory discrimination training is associated with improved reaction times. *Brain Res.* 1297, 80–88.

Towey, J., Rist, F., Hakerem, G., Ruchkin, D. S., and Sutton, S. (1980). N250 latency and decision time. *Bull. Psychon. Soc.* 15, 365–368.

van Praag, H., Kempermann, G., and Gage, F. H. (1999). Running increases cell proliferation and neurogenesis in the adult mouse dentate gyrus. *Nat. Neurosci.* 2, 266–270.

van Praag, H., Shubert, T., Zhao, C., and Gage, F. H. (2005). Exercise enhances learning and hippocampal neurogenesis in aged mice. *J. Neurosci.* 25, 8680–8685.

Verhaeghen, P., and Cerella, J. (2002). Aging, executive control, and attention: a review of meta-analyses. *Neurosci. Biobehav. Rev.* 26, 849–857.

Voelcker-Rehage, C., Godde, B., and Staudinger, U. M. (2011). Cardiovascular and coordination training differentially improve cognitive performance and neural processing in older adults. *Front. Hum. Neurosci.* 17:26. doi:10.3389/fnhum.2011.00026

West, R., and Travers, S. (2008). Differential effects of aging on processes underlying task switching. *Brain Cogn.* 68, 67–80.

Whitlock, J. R., Heynen, A. J., Shuler, M. G., and Bear, M. F. (2006). Learning induces long-term potentiation in the hippocampus. *Science* 313, 1093–1097.

WHOQOL Group. (1998). Development of the World Health Organization WHOQOL-BREF quality of life assessment. *Psychol. Med.* 28, 551–558.

Willis, S. L., and Schaie, K. W. (1986). Training the elderly on the ability factors of spatial orientation and inductive reasoning. *Psychol. Aging* 1, 239–247.

Willis, S. L., Tennstedt, S. L., Marsiske, M., Ball, K., Elias, J., Koepke, K. M., Morris, J. N., Rebok, G. W., Unverzagt, F. W., Stoddard, A. M., and Wright, E. (2006). ACTIVE Study Group. Long-term effects of cognitive training on everyday functional outcomes in older adults. *JAMA* 296, 2805–2814.

Wiskott, L., Rasch, M. J., and Kempermann, G. A. (2006). Functional hypothesis for adult hippocampal neurogenesis: avoidance of catastrophic interference in the dentate gyrus. *Hippocampus* 16, 329–343.

Zehnder, F., Martin, M., Altgassen, M., and Clare, L. (2009). Memory training effects in old age as markers of plasticity: a meta-analysis. *Restor. Neurol. Neurosci.* 27, 507–520.

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APPENDIX

DESCRIPTION AND SCHEDULE OF EXERCISES INCLUDED IN THE COGNITIVE TRAINING

The schedule of the cognitive training is presented in **Table A1**. **MAT** (www.gfg-online.de) is a paper and pencil package with short exercises which had to be applied for 10 min daily to increase working memory capacity, visual attention, and speed of information processing. In particular, the training aimed at enhancing psychomotor processing by faster perceiving and responding to objects or words, for example detection of triangles in a complex geometric figure or identification of words in a complex letter matrix, which were arranged either vertically, horizontally, or diagonally. Memory training included exercises that used words, figures, or digits. Participants were asked to memorize the items from each category and recall as many items as possible after several minutes. A more complex exercise consisted of association between faces and personal data like age and profession and recalling the information after a face presentation 10 min later.

The training begins with easy exercises to make quick effects possible. By creating more challenging instructions and by allowing less time for task performance, the level of difficulty gets enhanced gradually.

Table A1 | A schedule of the cognitive training program.

Week	Session	Exercise
1	1	MAT
	2	MAT
2	3	MAT
	4	MAT
3	5	MAT
	6	MAT/Sudoku
4	7	MAT/Sudoku
	8	MAT/Sudoku
5	9	Mental-Aktiv/Ahano/Sudoku
	10	Mental-Aktiv/Ahano
6	11	Mental-Aktiv/Ahano
	12	Mentaga/Mental-Aktiv/Ahano
7	13	Mentaga/Mental-Aktiv/Ahano
	14	Mentaga/Ahano
8	15	Mentaga/Ahano
	16	Mentaga/Ahano/Sudoku
9	17	Mentaga/Ahano/Sudoku
	18	Mentaga/Sudoku
10	19	Mentaga/Sudoku
	20	Mentaga/Sudoku
11	21	Mentaga
	22	Mentaga
12	23	Mentaga/Ahano
	24	Mentaga/Ahano
13	25	Mentaga/Sudoku
	26	Mentaga/Ahano
14	27	Mentaga/Ahano
	28	Mentaga/Ahano
15	29	Mentaga/Ahano
	30	Mentaga
16	31	Mentaga/Ahano/Sudoku
	32	Mentaga/Sudoku

The training consists of the following modules:

Information processing speed:
Time limited visual search. Different forms, numbers and letters are used. Identification of single words in randomly assembled sequences of letters. The hidden words are arranged forward, backward, vertically, horizontally, or diagonally.

Memory span:
Keep several numbers, words, or pictures in memory and immediate recall of words or identifying missing words.

Basic learning speed:
Memorization of faces with personal data and memorization of faces with distracting stimuli.

Mental-aktiv (www.mental-aktiv.de) is an internet-based platform that offers a number of memory tasks using digits, letters, colors, and figures and exercises to train speed of processing. The exercises were designed in cooperation with the authors of MAT and trained the same functions as listed above.

Sudoku is a logic-based number placement puzzle that consists from a 9 × 9 grid with digits so that each column, each row, and each of the nine 3 × 3 sub-grids contain all of the digits from 1 to 9.

Ahano peds (www.ahano.de) consists of units with different levels of difficulty. The free available program includes an eye-hand coordination task, money counting task, detection of word repetitions in a text, block taping task, memory for abstract figures etc.

Double:
There is a yellow ball and a red box presented on the screen. With one hand, the participant has to use the computer mouse in a certain way in order to put the ball into the box. With the other hand, the participant has to type the presented words as quickly as possible. This exercise trains peripheral visual attention as well as the coordination of multiple operations.

Euro Coins:
There are many different coins in a purse. The task is to assemble specific coins in order to reach a given amount. This should be done as often as possible within a specific interval. Visual perception, selective attention, and mental arithmetic are trained.

Response:
Balloons float past the window of an aircraft. The task is to click as quickly as possible on the relevant balloon appearing on the left side of the window. This exercise trains selective attention and distractor inhibition.

Palpation:
At the time when a green light appears on the screen, one of five given forms is hidden behind a big picture. The participant's task is to touch the form by use of the computer mouse in order to decide which form is hidden in the current trial. To make a choice, the participant has to click on the corresponding picture. There

is only one attempt in each trial. This exercise trains perception and spatial–visual memory.

Double Words:
A pool of words is given, which contains each single word twice. The task is to click on the currently relevant word by use of the computer mouse. There are five attempts in each trial to find the correct word. This exercise trains the participant's memory.

Chimpanzee test:
Nine fields are presented containing single digits for a short time. After the digit's disappearance, the participants are instructed to click on the fields in ascending order to reproduce the positions, where the respective figures were shown. Here, visual perception, short-term memory and spatial–visual memory can be trained.

Colors:
The participants have to memorize the colors of a presented picture. The task is to "repaint" the image by first clicking on a "paint pot" and then clicking on the image area. The participants receive one point for each correctly chosen color. Visual perception, short-term memory and spatial–visual memory can be trained by this exercise.

Mentaga (www.mentaga.com) consists of exercises enhancing vigilance, perceptual speed, spatial attention etc. like comparison of visual patterns, face learning, counting, vigilance, and eye-hand coordination

Figurative Thinking:
In each trial, two, almost identical pictures are presented. There are exactly three differences between the two pictures, which the participant has to detect as quickly as possible. This exercise is designed to support selective attention.

Capacity:
The task is to catch vertically falling balls with a basket as accurately and quickly as possible. To adjust the basket, the participant has to use the computer mouse. Simultaneously, as many numerical and alphabetical tasks as possible have to be performed. Spatial–visual attention, arithmetic, concentration, and of multiple task performance should be improved by this task.

Concentration:
In each trial, an "E" surrounded by a certain number of dots is presented. The task is to identify every E which is surrounded exactly by three dots as quickly as possible. Concentration and visual attention are trained by this task.

Pattern Matching:
Four pictures are presented in each trial. There is always one original, two rotated versions of the original and one differing picture, which the participant has to identify by clicking on it. This exercise trains the abilities of mental rotation and visual search.

Person Memory:
This exercise aims at memorizing and recognizing names and faces. First, a sequence of faces and names is presented and the participants explicitly have to memorize the names. Then, faces are displayed with various names. The participant has to decide which name is related to a particular face. This exercise specifically trains object recognition.

Visual Acuity:
In each trial, two pictures are presented. As quickly as possible, the participant has to decide whether the two pictures are identical. Visual acuity and visual search are trained by this task.

Response Capacity:
Two objects are presented side by side. The participant has to decide whether the objects are identical. A response is required if the objects are identical. This exercise aims at improving visual search and decision time.

Memory for Numbers:
The participant has to memorize and reproduce numbers presented on the screen. The length of each number is adapted to the participant's capacity. The more digits a number contains, the more time is granted for memorizing and reproducing the number. Primarily, this exercise trains the memory for numbers, but also working memory in general.

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Intraindividual reaction time variability is malleable: feedback- and education-related reductions in variability with age

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Intraindividual variability (IIV) in trial-to-trial reaction time (RT) is a robust and stable within-person marker of aging. However, it remains unknown whether IIV can be modulated experimentally. In a sample of healthy younger and older adults, we examined the effects of motivation- and performance-based feedback, age, and education level on IIV in a choice RT task (four blocks over 15 min). We found that IIV was reduced with block-by-block feedback, particularly for highly educated older adults. Notably, the baseline difference in IIV levels between this group and the young adults was reduced by 50% by the final testing block, this advantaged older group had improved such that they were statistically indistinguishable from young adults on two of three preceding testing blocks. Our findings confirmed that response IIV is indeed modifiable, within mere minutes of feedback and testing.

Keywords: intraindividual variability, aging, reaction time, performance variability, feedback, cognitive reserve

INTRODUCTION

Moment-to-moment intraindividual variability (IIV) often refers to relatively rapid fluctuations in task performance (see Hultsch et al., 2008; MacDonald et al., 2009a). Particularly with regard to reaction time (RT) measured in a variety of cognitive domains (e.g., simple and choice RT tasks), older adults are typically more inconsistent than younger adults in their response patterns from trial to trial (Hultsch et al., 2008). Evidence suggests that trial-to-trial variability can offer unique predictive utility over and above mean performance level when predicting both normal (e.g., Williams et al., 2005; Lövden et al., 2007) and non-normal aging (e.g., Hultsch et al., 2000; Dixon et al., 2007). IIV is effectively a proxy measure representing a host of complex and dynamic influences and processes. Among several possible cognitive and neural [structural (e.g., lesions); functional (e.g., reduced brain signal dynamics); neuromodulatory (e.g., dopamine degradation); genetic (e.g., val variant of the catechol *O*-methyltransferase gene)] mechanisms mediating and moderating age-related IIV (MacDonald et al., 2006b, 2009b; Garrett et al., 2011), response variability is thought to partially reflect degradations in age-related frontal lobe-(see Stuss et al., 1994, 2003; MacDonald et al., 2009a) and broader task positive network-mediated cognitive functions (Kelly et al., 2008) such as attention allocation or cognitive control (Bunce et al., 1993; West et al., 2002; Stuss et al., 2003; Duchek et al., 2009; Jackson et al., 2012). Critically, age-based behavioral analyses of the Ex-Gaussian RT distribution suggest that the IIV effect is caused primarily by excessively slow within-person response latencies (West et al., 2002; Williams et al., 2005), possibly a result of momentary lapses in attentional control.

Findings suggesting that neural integrity and efficiency are required for consistent RT performance prompt the question as to whether it is possible to *experimentally manipulate* IIV in older adults, despite nervous system degradation. Given that attention/control systems are implicated in age-related IIV, these systems may be appropriate targets for attempts to reduce IIV. Evidence suggests that attention/control can improve with effective intrinsic (e.g., a participant's interest in the task) and extrinsic (e.g., external incentives such as points or money) attentional motivation or goal-direction on task (e.g., Tomporowski and Tinsley, 1996; Libera and Chelazzi, 2006; Bengtsson et al., 2009). Ongoing extrinsic motivators may be of particular interest because they can serve as an immediate source of within-task feedback, informing participants of their past and present levels of task performance, and prompting them to adjust their strategic approach if point levels are lower than desired. If IIV does reflect deficits in attention and control, employing methods that improve such deficiencies in older adults may also reduce IIV by limiting overly long response latencies. In addition, goal-directed feedback and training may serve as forms of direct external stimulation and environmental support for healthy older adults (Craik, 1983, 1986), from which task performance can improve and even approach younger adult levels (Naveh-Benjamin et al., 2005). Craik (1983, 1986) argued that by utilizing environmental support, one can alleviate demands on already limited processing/attentional resources; alleviating these demands through performance feedback could be critical for optimizing the consistency of RT responses in older adults.

Another important factor in the context of IIV, feedback, and aging may be level of education, which provides a measure of one's learning ability and intelligence, as well as one's level of cognitive reserve (Stern, 2002). "Cognitive reserve" refers to the point that higher educated older adults are often less susceptible to cognitive impairment, and thus maintain higher levels of cognitive performance compared to their less well-educated peers. Individuals with high cognitive reserve may exhibit less cognitive impairment over time, in part, because they may devise and implement alternative strategies for completing tasks when the methods they employed previously are no longer effective. Essentially, this may represent a willingness or ability to apply different approaches to the same problem. Higher educated adults may thus respond more effectively to feedback paradigms that directly impact their performance. This possible manifestation of reserve may also indicate *cognitive flexibility* (Lövden et al., 2010), which reflects one's ability to utilize existing functional capacities to rapidly adapt to changing environmental and cognitive demands. Further, better educated older adults may exhibit superior attentional allocation in general (e.g., Tun and Lachman, 2008), possibly yielding lower IIV (Christensen et al., 2005), and allowing a more focused and sustained response to goal-direction and feedback. It thus seems possible that feedback-related impacts on IIV may vary by education level.

In the current study, we examined the effects of goal-directed feedback, age, and education on trial-to-trial IIV over multiple blocks of a four-choice RT task. We anticipated that feedback would reduce IIV by providing motivation and focusing attentional resources on specific aspects of the task, particularly in our highly educated participants. Given older adults' typically greater level of IIV, and younger adults' already superior patterns of response consistency, we expected that older adults would benefit most from feedback. We also examined the effect of feedback, age, and education on mean speed to gauge differences between IIV and mean RTs in our paradigm. Importantly, previous research suggests that IIV and mean RT levels can improve simply through task exposure (i.e., in absence of feedback; e.g., Ram et al., 2005; Ratcliff et al., 2006; Dutilh et al., 2009; Schmiedek et al., 2009). Accordingly, all subjects in our paradigm received the same amount of task exposure, which allowed us to control for any practice-related improvements in IIV while examining the effects of age, feedback, and education level.

MATERIALS AND METHODS

PARTICIPANTS

We recruited 41 healthy undergraduates (18–34 years) from the University of Toronto ($M_{\text{age}} = 21.56$ years, $SD_{\text{age}} = 3.70$; $M_{\text{education}} = 14.22$ years, $SD_{\text{education}} = 1.82$) and 57 healthy, community-dwelling older adults (60–82 years) from Toronto and surrounding communities ($M_{\text{age}} = 70.95$ years, $SD_{\text{age}} = 4.94$; $M_{\text{education}} = 16.06$ years, $SD_{\text{education}} = 2.18$; unfortunately, reliable information on ethnicity/nationality was not available for the current sample). Young adults received course credit and older adults received $15 for their participation. The Office of Research Ethics at the University of Toronto approved the current study.

TASK

We administered a four-choice RT task that contained four blocks of trials, and 40 trials per block. Participants were shown four white squares (2″ × 2″ each) in a horizontal line on a black background on a 15″ laptop computer screen. When one of the squares turned red, participants were asked to press one of four buttons on a response box corresponding to the location of the red square. To encourage consistent attentional allocation throughout each block, participants were instructed to make consistently quick and accurate responses. We utilized a continuous RT task format that required correct response button presses; the next stimulus appeared immediately (and only) after a correct response was made, without any interstimulus interval. As such, accuracy for each participant was guaranteed to be 100%. Continuous RT tasks may provide more intrinsic attentional motivation than ISI-based RT tasks, as participants can progress through such tasks at a pace that matches their performance level (Hazlett et al., 2001).

Four-choice RT tasks have proved useful in models that relate IIV to both age and cognitive status (e.g., Hultsch et al., 2002; Dixon et al., 2007), and a host of other studies have also successfully employed a number of variants of the choice RT paradigm in IIV research (e.g., Shammi et al., 1998; Rabbitt et al., 2001; Murtha et al., 2002; Anstey et al., 2005; Williams et al., 2005). Our decision to use four-choice rather than the more typical two-choice paradigm was based on previous research suggesting that age differences can become more marked (i.e., greater between-group variance) when greater processing requirements are placed upon participants (West et al., 2002). Further, it was important that the task not be too difficult in order to promote participant motivation and engagement on task. The four-choice option seemed reasonable to avoid both floor and ceiling effects, while providing enough difficulty to allow improvement over blocks to occur.

PROCEDURE AND FEEDBACK PARADIGM

Half of each age group received feedback and the other half did not (participants were randomly assigned). Participants receiving feedback were told prior to the beginning of the paradigm that they would receive 10 points for each *consistently quick* response, lose 10 for a *somewhat slow* response, lose 20 for a *very slow* response, and lose 50 for an *extremely slow* response. Feedback was provided immediately after each block of 40 trials. Participants were shown three types of feedback at each feedback occasion. First, we plotted the distance of each of the 40 trials from the within-subject median of the immediately preceding block (on the first feedback block, it was necessary to use the block 1 median). Any trial on which participants responded +0.5 standard deviations (SDs) or quicker in relation to their own median, they were awarded 10 points (see green zone in **Figure 1A**). Participants lost 10 points for responses from +0.5 to +2 SDs (yellow zone), lost 20 points for responses from +2 to +4 SDs (orange zone), and lost 50 points for responses from +4

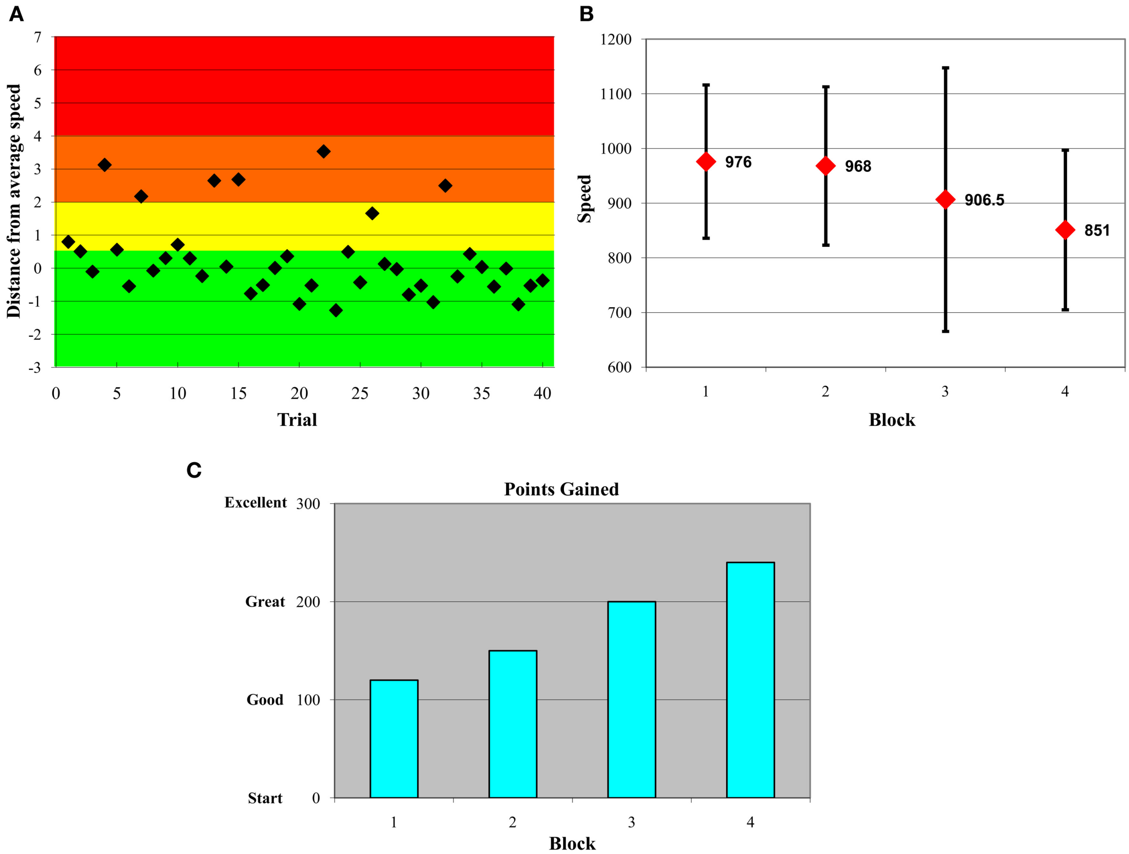

FIGURE 1 | Variability-reduction feedback plots. All participants in the feedback condition were shown plots such as these in serial order. Plots **(A–C)** represent data from an example participant. **(A)** Within-block trial-by-trial performance feedback plot. Participants were awarded 10 points if a trial response was in the green zone, −10 if in the yellow zone, −20 if in the orange zone, and −50 if in the red zone. The *y*-axis represents numbers of standard deviations from a participant's own median from the previous block. **(B)** Feedback plot of response time medians and SDs across blocks. **(C)** Feedback plot of points gained across blocks.

to +7 SDs (red zone) above their own median in the preceding block. Using the immediately preceding median provided a "moving target" that encouraged continuous improvement throughout the entire task. Importantly, although abnormally fast responses also mathematically increase indices of response inconsistency, evidence suggests that it is overly slow trials that often yield group differences in inconsistency (cf. West et al., 2002). Thus, we deliberately discouraged participants' slower responses in the current feedback paradigm by only penalizing point values for higher RTs. In any case, unrealistically quick responses were also trimmed prior to statistical model runs in the current paper (see details on RT data preparation below).

This first feedback plot (shown in **Figure 1A**) also facilitated provision of feedback on overall patterns of inconsistent responses within-block and -person. For example, some participants were inconsistent at the beginning of a block of trials; in this case, we would emphasize to the participant that, on the next block of trials, they should focus their attention from the very first trial in an attempt to reduce their response variability. The second feedback graph plotted participants' median response time and their SDs for each block (see **Figure 1B**). This allowed participants to gauge their progress with regard to improved speed and consistency across blocks. The third feedback graph (see **Figure 1C**) plotted points gained across blocks, referencing the trial-by-trial points-based feedback plots shown initially during feedback (see **Figure 1A**). To maintain task motivation, the *y*-scale on this plot went from "Start" to "Good" to "Great" to "Excellent," and was designed deliberately to avoid any negative feedback. Critically, feedback was designed to reflect within-subject performance, and this ensured that participants attempted to improve relative to their own level of functioning. Participants were also encouraged to ask questions about their performance, and to propose ideas for their own improvement (which testers commented upon); this fostered an interactive dynamic between participant, tester, and feedback material. If participants' ideas were not logical, feasible, or permitted (e.g., "should I press all buttons rapidly to ensure correct answers?"), testers dissuaded participants from proceeding in that fashion. Most often, following feedback, participants appeared relatively aware of what they could do on the next block of trials to improve; as a result, testers were more positive and supportive than dissuasive. The paradigm (four blocks of 40 trials) took approximately 5 min for the Control groups (those not receiving feedback), and 10–15 min for the Feedback groups.

RT DATA PREPARATION

To prepare the RT data prior to ISD calculation, we adopted an approach employed previously (Hultsch et al., 2000, 2008; Dixon et al., 2007). First, extremely fast or slow responses could reflect common types of key press errors (e.g., accidental key press, interruption of the task), and thus, a lower bound for legitimate responses (150 ms) was set for each RT task on the basis of minimal RTs suggested by prior research (see MacDonald et al., 2006a; Dixon et al., 2007). An initial upper bound was determined by examining frequencies of RTs and trimming extreme outliers relative to the rest of the sample; we dropped all scores above 4000 ms. Following initial upper-bound trims, we proceeded to drop all trials exceeding within-subject block means by ± 3 SDs. The proportion of trials dropped and trimmed across the entire Persons × Trials data matrix was minimal; of 15,680 total trials, we trimmed only 187 (1.19%). The range of missing trials across subjects (range = 0.00–3.75%) was also minimal. To maintain complete data, we imputed trimmed values for outlier trials by using a regression imputation procedure (as implemented in SPSS 18.0) from which missing value estimates were based on the relationships among responses across trials from all participants.

INDEX OF IIV

Although there are multiple indices of IIV (see Hultsch et al., 2008), we employed the ISD. Importantly, computation of the ISD permits the researcher to systematically separate confounds of relevance in aging (e.g., age and practice effects). Computing ISDs on raw scores can be problematic; significant group differences in average level of performance are typically observed, and such differences are often positively correlated with differences in raw SD values. In addition, systematic changes across trials may be present (e.g., practice, learning effects). To address these potential confounds, we used a regression procedure developed by Hultsch et al. (Hultsch et al., 2000, 2008) to residualize the RT data prior to calculating ISDs. Using a person × trial data matrix (i.e., the data were structured in person-period format), we employed multiple regression to partial age group, feedback, education, and occasion effects (trials and blocks) and all interactions by regressing four-choice RT on these potential confounding variables. Then, within-person SDs (i.e., ISDs) were computed for each block using the choice-RT trial-based residuals from our regression model.

STATISTICAL ANALYSES

In a balanced design (all participants had complete data for all four blocks), we ran separate repeated-measures general linear models, in which we examined: (1) the ISD of all four blocks in relation to age group (young vs. old), feedback group (feedback vs. no feedback), years of education (continuous variable), and all interactions, and; (2) the mean RT of all four blocks in relation to the same covariates (age group, feedback, education, and all interactions). Because education was entered in our models as a continuous variable, and feedback and age group were categorical, we adapted a common approach to plotting categorical × continuous interactions (Aiken and West, 1991) for use with repeated measures modeling. Parameter estimates derived from a regression at each block (i.e., regressing ISD at each block separately on age, feedback, education, and their interactions) were utilized to plot average point estimates for specific levels within the interaction (e.g., in an Age × Feedback × Education interaction). In line with Aiken and West, all interactions that involved Education (a continuous variable) were evaluated at low (−1 SD from the sample mean, 13.42 years) and high (+1 SD from the sample mean, 17.64 years) levels of education. Then, once all point estimates were determined for each block, within-interaction-level point estimates were joined across blocks to visualize group slopes. We then proceeded to bootstrap these point estimates to derive 95% confidence intervals (CIs; percentile method; Efron and Tibshirani, 1986, 1993) using 1000 resamples (with replacement) of our data. These CIs allowed us to compare point estimates within and across blocks. For ease of reporting throughout, we refer to levels of each interaction as "groups" [e.g., an older, feedback, high educated (OFH) group] even though education (continuous) was part of the interaction and was evaluated at ±1 SD from the sample mean. SPSS 18.0 was employed for all analyses.

RESULTS

ISD ANALYSES

We found several robust interactions, most notably, a Block × Age × Feedback × Education effect (see **Table 1** for model results and **Figure 2A** for a visual depiction). To further examine this interaction, we first ran separate Block × Feedback × Education models for each age group (see **Table 1**). There were no significant effects in the young group (all p's > 0.48), suggesting that neither Feedback nor Education had an impact on ISD scores. However, in older adults, all effects were substantial, with estimates of effect size (*partial* η^2) greater than 0.35 for each effect (see **Table 1**). To *post-hoc* probe differences between point estimates plotted in **Figure 2A**, we computed bootstrapped 95% confidence intervals (1000 model runs, using resampling with replacement) around each estimate for older adults (given significant main effects and interactions within this group), and for the younger group as a whole (given a complete absence of robust differences between point estimates across blocks). We were particularly interested in differences in ISD values at, or in relation to, Block 4, as this block represented participants' final chance at performance after the maximum amount of possible feedback exposure (i.e., for Feedback groups). Key Block 4 comparisons revealed that following the final session of performance feedback, the OFH group exhibited more consistent performance than either the older, control, low educated (OCL) or older, control, high educated (OCH) groups (i.e., bootstrapped 95% CIs did not cross over; see **Figure 2A**). Most importantly, the OFH group had improved by Block 4 to the extent they were statistically indistinguishable from the young group at either of Blocks 1 or 3. Despite overall reductions in ISDs across blocks, no other older group approached the young group at any Block.

Descriptively, the OFH group closed the gap in ISD levels between them and the young group by a substantial margin by Block 4. The difference in ISDs between young and OFH groups at Block 1 was exactly 50% smaller at Block 4, nearly 11% better than the next best older group (the OCH group, see **Table 2**). The OFH group also showed the greatest within-group improvement

Table 1 | Repeated-measures model results of ISD- and mean RT-based analyses.

		Multivariate		
		F	***p***	**Partial η^2**
ISD (whole sample)	Block	0.19	0.91	0.01
	Block × Age group	4.12	0.01	0.12
	Block × Feedback	0.05	0.98	0.00
	Block × Education	0.28	0.84	0.01
	Block × Age group × Feedback	6.05	<0.0001	0.17
	Block × Age group × Education	3.71	0.02	0.11
	Block × Feedback × Education	0.07	0.98	0.00
	Block × Age group × Feedback × Education	5.55	<0.0001	0.16
ISD (old only)	Block	9.97	<0.0001	0.37
	Block × Feedback	9.14	<0.0001	0.35
	Block × Education	11.34	<0.0001	0.40
	Block × Feedback × Education	9.48	<0.0001	0.36
Mean RT (whole sample)	Block	0.30	0.83	0.01
	Block × Age group	2.69	0.05	0.08
	Block × Feedback	0.50	0.68	0.02
	Block × Education	0.25	0.86	0.01
	Block × Age group × Feedback	1.81	0.15	0.06
	Block × Age group × Education	1.98	0.12	0.06
	Block × Feedback × Education	0.51	0.67	0.02
	Block × Age group × Feedback × Education	1.75	0.16	0.06

ISD, intraindividual standard deviations; RT, reaction time.

between Blocks 1 and 4 (34% reduction in ISD scores) relative to other older groups (see **Table 2**). The OCL group was noticeably poorer, showed the least improvement across blocks (9.32%), and remained the furthest from Young adult performance of all older groups by nearly 30%.

MEAN RT ANALYSES

Unlike for our ISD analyses, we found only a single reliable effect in our mean RT-based Block × Age Group × Feedback × Education model (see **Table 1**). A modest Block × Age Group interaction was present ($p = 0.051$; partial $\eta^2 = 0.08$), which denoted a slightly increased rate of mean RT improvement over blocks for the older groups (see **Figure 2B**). For all blocks, all older subgroups were statistically different from young adults.

DISCUSSION

In the current study, we examined the effect of interactive, goal-directed feedback on reductions in response time variability in younger and older adults. We anticipated that such feedback would reduce IIV by providing motivation and focusing attentional resources on task, and would specifically inhibit overly slow responses that typically underlie variability effects (West et al., 2002; Williams et al., 2005) by providing environmental support (i.e., feedback) to alleviate strains on processing resources (Craik, 1983, 1986). We also anticipated that higher educated older adults (education was used as a proxy measure for cognitive reserve; Stern, 2002) would be more likely to benefit from feedback, possibly due to their willingness to adopt different strategies on task (which our feedback paradigm could have helped provide), or due to their typically superior attentional abilities (which may have allowed a more sustained and focused response to performance feedback). Indeed, we confirmed substantial feedback-related reductions in IIV for older adults, most prominently for those with higher education. This suggests that IIV was significantly malleable for this group as a result of relatively short, incentive-based, interactive visual and auditory feedback. This effect was surprisingly strong even though feedback and task blocks took only 10–15 min to administer, effectively eliminating differences between the OFH group and young adults on two of the four blocks of measurement. Thus, although IIV can be a stable within-person trait (e.g., Hultsch et al., 2008), our findings indicate that age-related IIV is certainly modifiable, even within a remarkably short period of feedback and testing. Further, all our groups had the same amount of task exposure/practice (4 block of 40 trials each); thus, the OFH group reduction in IIV was present over and above typical practice-related improvements noted in previous work (e.g., Ram et al., 2005; Ratcliff et al., 2006; Dutilh et al., 2009; Schmiedek et al., 2009).

Our OCL group showed the least performance gains across blocks. This is interesting given that "low" education was evaluated at 13.42 years (the lower bound for our sample was 12 years), hardly low by epidemiological standards. It thus appears that reliable individual differences in ISD malleability exist even within a sample of only those with high school education or more. Also of note, young adults did not respond to feedback, and were relatively consistent across all four task blocks. It is typical and expected for young adults to perform relatively consistently on RT tasks such as the one we employed in the present study (e.g.,

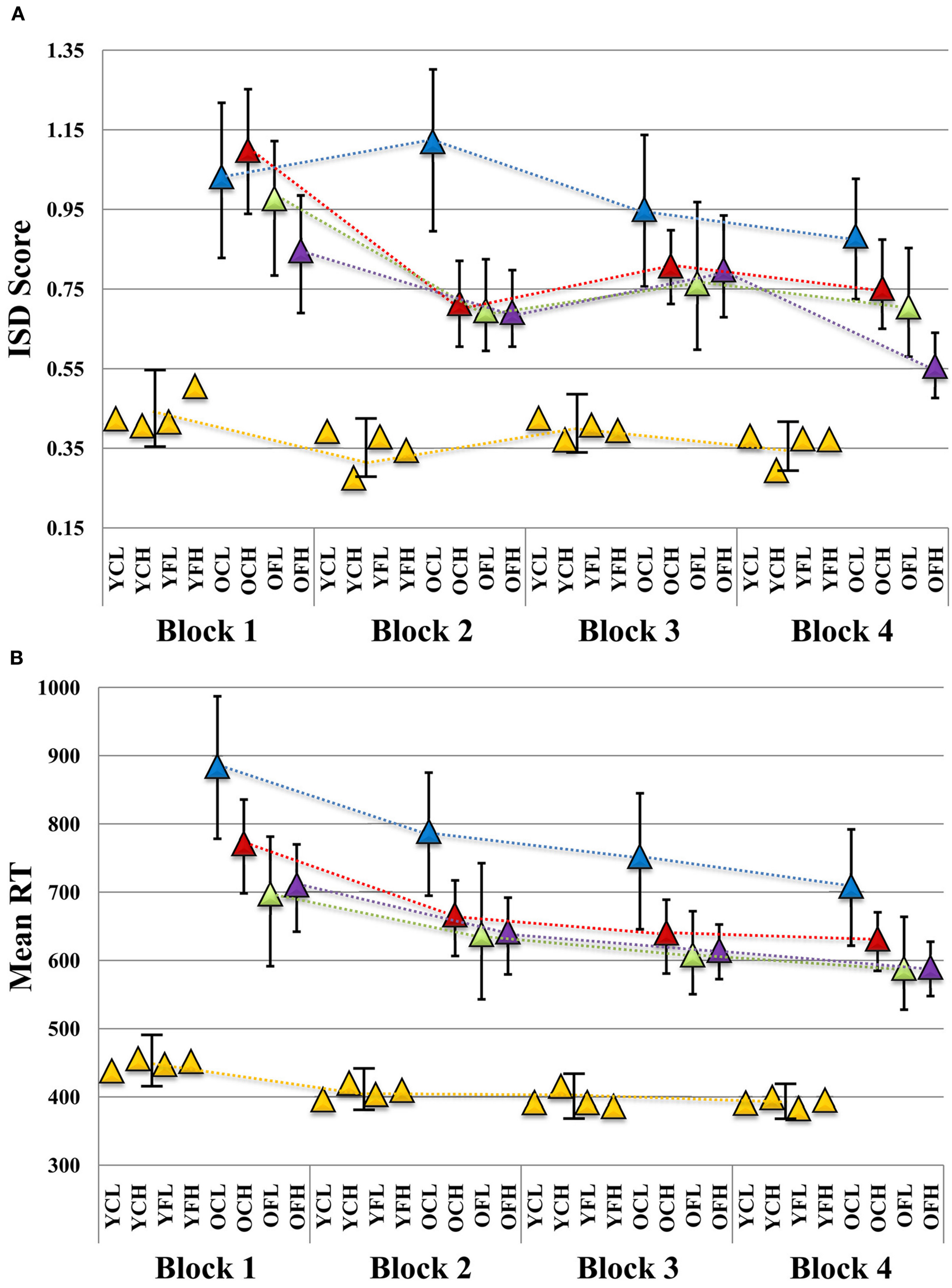

FIGURE 2 | Plot of block-wise (A) ISD and (B) mean RT results in relation to age, feedback, and education level. ISD, intraindividual standard deviation; YCL, younger, control, lower education; YCH, younger, control, higher education; YFL, younger, feedback, lower education; YFH, younger, feedback, higher education; OCL, older, control, lower education; OCH, older, control, higher education; OFL, older, feedback, lower education; OFH, older, feedback, higher education. All slopes were plotted according to Aiken and West's (1991) method. Using betas for each block (including all main effects and interaction terms), point estimates were determined while evaluating education at +1 SD (17.64 years) and −1 SD (13.42 years) from the sample mean, and dummy coding age (young vs. old) and feedback (control vs. feedback) groups. Triangles indicate point estimate values. Error bars for each point estimate refer to bootstrapped 95% confidence intervals derived from 1000 resamples (with replacement) of our original data ($N = 98$). Where bars do not overlap, this indicates a robust bootstrapped difference between point estimates. **(A)** Given no differences between young adult subgroups in any of our results (all young model effect p's > 0.48; see Results), we provide a single young group bootstrapped CI per block for comparison to older subgroups. **(B)** A similar plot is provided for mean RT.

Table 2 | Proportionate improvements in ISDs for older groups.

	Reduction in young-old ISD differences at Block 4 relative to Block 1 (%)	Within-group ISD reduction by Block 4 (%)
OFH	50.00	34.12
OFL	36.11	28.57
OCH	39.23	31.19
OCL	9.32	13.59

OFH, older, feedback, higher education; OFL, older, feedback, lower education; OCH, older, control, higher education; OCL, older, control, lower education. The first column of values indicates the within-group percentage improvement at Block 4 relative to Block 1. The second column of values indicates a "difference of differences"; we subtracted the difference between Young-Old group ISDs at Block 4 from the Young-Old group ISD difference at Block 1, and the percentage reduction at Block 4 is noted here.

Hultsch et al., 2002; West et al., 2002; Williams et al., 2005). The processing resources required for young adults to perform quickly and consistently on such tasks are relatively minimal compared to older adults, perhaps indicating a functional bound where feedback would have little or no effect on further ISD reductions. This is supported by previous work showing that young adults' RT variability improves relatively little with practice (e.g., Ratcliff et al., 2006). However, it is also possible that our feedback paradigm simply wasn't optimized for younger adults to improve on already excellent levels of performance, or that our choice RT task was too simple for feedback to have any notable effect. Follow-up paradigms and task types may address these issues.

ISDs vs. MEAN RTs

We observed several systematic age-, feedback-, and education-related effects that could not be captured using mean RT; the mean was simply less sensitive to these block-to-block changes. In line with several previous studies, this suggests that IIV continues to offer differential and unique information regarding RT performance (see Hultsch et al., 2008; MacDonald et al., 2009a; Schmiedek et al., 2009), and can be targeted directly by feedback. In several contexts, IIV is more sensitive than mean RT when relating to a variety of phenomena, including normal aging and mild cognitive impairment (e.g., Dixon et al., 2007) and developmental increases in brain variability (McIntosh et al., 2008). In general, IIV measures may reveal theoretically important aspects of cognitive function that cannot be captured by measure of central tendency (Spieler et al., 2000), such as age-related lapses in attentional control (Bunce et al., 1993; West et al., 2002; Stuss et al., 2003; Duchek et al., 2009; Jackson et al., 2012) rather than overall psychomotor slowing. Unsurprisingly, the utility of examining IIV extends to non-cognitive domains as well. For example, recent work suggest that brain signal variability is a far more powerful and sensitive predictor of aging than is mean signal, and highlights a broad set of regions that are not detectable by examining only mean-based patterns (Garrett et al., 2010, 2011). Thus, examining IIV across scientific lines of inquiry continues to offer a variety of meaningful sources of information about the aging process that mean-based measures cannot provide.

TARGETING THE COGNITIVE AND NEURAL COMPONENTS OF IIV

Given the nature and design of our paradigm, our findings give credibility to arguments that performance variability may partially reflect failures of attentional control (see Bunce et al., 1993; West et al., 2002). By specifically providing environmental support (cf. Craik, 1983, 1986) via feedback to reduce overly slow trials that presumably result from attentional lapses, we can reduce variability (for an alternative, but related theoretical account reflecting "processing efficiency" rather than attentional lapses, see Ratcliff et al., 2006, 2008; Dutilh et al., 2009). Although aging-related response variability reflects various endogenous neural mechanisms such as degraded white matter integrity (e.g., Jackson et al., 2012; Tamnes et al., 2012), reduced brain variability and dynamics (Garrett et al., 2011), and inefficient neuromodulatory transmission (see MacDonald et al., 2006b, 2009a), the rapid improvements in ISD levels we found suggest that it is possible to maximize one's existing neural substrate by providing cognitively oriented feedback and motivation on task. Unsurprisingly, higher educated (reserve) older adults were most able to maximize their functional capacity by effectively applying feedback to improve performance, perhaps through a greater level of cognitive *flexibility* (Lövden et al., 2010) and/or a willingness to apply different cognitive approaches to performance (Stern, 2002).

It could be argued that the rapid reductions in IIV our data are divergent from previous research indicating that performance variability is a function of nervous system integrity/efficiency. That is, if our paradigm can improve IIV over a few minutes, can nervous system integrity/efficiency really be an effective mechanistic explanation? We would argue that our results do not directly detract from IIV-nervous system links. Of course, rapid improvements in IIV would not reflect immediate changes in structural integrity (e.g., white matter) or genetic expression (e.g., val or met variants of COMT). However, changes in efficiency at the functional/network level are certainly possible over short periods. The human brain is a highly dynamic structure, within which functional networks form and change naturally from moment to moment across multiple time scales, despite the presence of a stable white matter skeleton (Honey et al., 2007, 2009). Although we do not present neuroimaging data in the current study, it is conceivable that attention/control-related functional networks (e.g., Kelly et al., 2008) may operate more efficiently over minutes (possibly as a result of top-down modulation following feedback and task exposure), particularly in our OFH group. However, whether further training blocks/task exposure would fully counteract older age- and lower education-related network inefficiencies remains unknown, but is doubtful. Functional changes will always be bounded, even if relatively liberally, by stable elements within the system (e.g., age-related degradations in brain structure). Regardless changes in IIV must be represented within the brain, and relatively rapid functional change is the most obvious candidate.

ON THE NON-LINEAR TRENDS ACROSS BLOCKS

Three of our four older subgroups exhibited a similar non-linear trend across blocks in which an initial burst of improvement after the first feedback occasion (at Block 2) was followed by an uptick in variability at Block 3, and another reduction in variability by Block 4 (to a lesser extent, this trend was similarly noticeable in the young adult subgroups; see **Figure 2A**). Along a different trajectory, our poorest performing group (older low educated controls) also showed fluctuations in gains and losses across blocks. Although it may appear somewhat surprising that such fluctuations in across-block variability could occur (particularly the uptick from Blocks 2 to 3), this pattern may be expected. During the acquisition and improvement/practice of cognitive performance, greater variability can indicate an adaptive process indicative of learning, as well as strategy development, employment, and adjustment. Only when asymptotic performance is reached is further variability considered maladaptive (Siegler, 1994; Li et al., 2004). From this perspective, one could predict that our OFH group (with a combination of cognitive reserve, goal-directed feedback, and possible resulting strategy modifications) may continue to appear variable in their level of *across*-block ISD performance over multiple successive blocks than would other older groups. The OFH group did exhibit the most extreme change from Blocks 3 to 4, whereas the other three older groups exhibited a similarly modest change in slope across these two blocks (see **Figure 2A**), perhaps indicating a more rapidly approaching performance asymptote for them. In any case, across-block variability in within-block performance may be expected until an asymptote is reached, regardless of feedback paradigm, task, or sample.

POTENTIAL CAVEATS AND FUTURE RESEARCH POSSIBILITIES

First, the various practical implications of, and precise mechanisms driving, our results require future study. Regarding practical implications, issues central in many cognitive training/feedback studies often include: (1) the possibility of functional improvement in older adults' lives; (2) the presence of "far transfer" (i.e., that training in one cognitive domain yields gains in another domain, and; (3) the longevity of training-related gains (i.e., do gains last minutes, days, weeks, months?). Regrettably, we cannot directly address any of these issues with our present data. Our primary intention here was only to examine whether IIV was malleable in the short-term using a targeted feedback paradigm in the context of young and older adults of differing education levels. Also, because age and education are multiply determined proxy measures that represent a host of different cognitive, neural, and physical processes, the precise mechanisms driving our findings require further characterization. We thus offer our present paradigm and results as a first look at the feedback-related malleability of IIV.

Second, to fully appreciate the impact of age, feedback, and education on reductions in IIV, future studies could employ paradigms with a greater number of testing blocks. Although our brief paradigm revealed several interesting effects that were verified via 1000 unbiased, bootstrapped model runs, it would be ideal to establish the IIV asymptote for each group, and whether all older groups, or only the OFH group, ultimately approach young adult levels of performance. Previous work examining IIV on a three-back spatial working memory task over 100 daily sessions established that older adult IIV levels largely asymptote after approximately five or six sessions (Schmiedek et al., 2009); whether this same number of sessions would also produce an asymptote within a single day, multi-block, multi-group paradigm such as ours remains unknown.

Finally, to better understand how older adult IIV reduces with practice, feedback, and education levels, future work could pursue how IIV malleability is reflected in changes in brain function (as noted above). For example, previous research (Kelly et al., 2008) indicated that greater RT IIV can reflect less efficient transitions (and lower anti-correlations) between default mode (a primary resting-state network that activates largely in absence of externally demanded attention) and task positive network functioning (a network active upon externally demanded attention). It would be interesting to examine whether our across-block reductions in IIV may be reflected in greater default mode-task positive network anti-correlations. Also, recent aging-related research demonstrated that higher RT variability was robustly related to *lower* brain signal variability across perceptual matching, attentional cueing, and delayed match-to-sample tasks (Garrett et al., 2011). It is thus plausible that reductions in IIV across blocks may covary with increases in brain signal variability. A host of studies now support the point that greater brain variability can be an excellent indicator of well-functioning neural systems, reflecting features such as greater network complexity, system criticality, long-range functional connectivity, increased dynamic range and information transfer, and heightened signal detection (e.g., Li et al., 2006; Faisal et al., 2008; McIntosh et al., 2008, 2010; Shew et al., 2009, 2011; Garrett et al., 2010, 2011; Deco et al., 2011; Misic et al., 2011; Vakorin et al., 2011). A direct manipulation of both behavioral and brain variability would not only be an excellent test of their covariance, it would also be helpful for establishing which neural regions best exhibit adjustments in neural dynamics to brief, cognitively oriented feedback paradigms such as ours.

CONCLUDING REMARKS

In the current study, we employed a novel, goal-directed, and interactive feedback paradigm designed to attenuate IIV in response time through a hybrid of extrinsic motivation and heightened attentional allocation/control on task. Our findings suggest that response IIV is indeed modifiable, but that the beneficial effects of feedback may be specific to age group and level of education.

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REFERENCES

Aiken, L. S., and West, S. G. (1991). *Multiple Regression: Testing and Interpreting Interactions.* Thousand Oaks, CA: Sage.

Anstey, K. J., Dear, K., Christensen, H., and Jorm, A. F. (2005). Biomarkers, health, lifestyle, and demographic variables as correlates of reaction time performance in early, middle, and late adulthood. *Q. J. Exp. Psychol. A* 58, 5–21.

Bengtsson, S. L., Lau, H. C., and Passingham, R. E. (2009). Motivation to do well enhances responses to errors and self-monitoring. *Cereb. Cortex* 19, 797–804.

Bunce, D. J., Warr, P. B., and Cochrane, T. (1993). Blocks in choice responding as a function of age and physical fitness. *Psychol. Aging* 8, 26–33.

Christensen, H., Dear, K. B. G., Anstey, K. J., Parslow, R. A., Sachdev, P., and Jorm, A. F. (2005). Within-occasion intraindividual variability and preclinical diagnostic status: is intraindividual variability an indicator of mild cognitive impairment? *Neuropsychology* 19, 309–317.

Craik, F. I. M. (1983). On the transfer of information from temporary to permanent memory. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* 302, 341–359.

Craik, F. I. M. (1986). "A functional account of age differences in memory," in *Human Memory and Cognitive Capabilities, Mechanisms and Performance*, eds F. Klix and H. Hagendorf (Amsterdam: Elsevier), 409–422.

Deco, G., Jirsa, V. K., and McIntosh, A. R. (2011). Emerging concepts for the dynamical organization of resting-state activity in the brain. *Nat. Rev. Neurosci.* 12, 43–56.

Dixon, R. A., Garrett, D. D., Lentz, T. L., MacDonald, S. W. S., Strauss, E., and Hultsch, D. F. (2007). Neurocognitive markers of cognitive impairment: exploring the roles of speed and inconsistency. *Neuropsychology* 21, 381–399.

Duchek, J. M., Balota, D. A., Tse, C. S., Holtzman, D. M., Fagan, A. M., and Goate, A. M. (2009). The utility of intraindividual variability in selective attention tasks as an early marker for Alzheimer's disease. *Neuropsychology* 23, 746–758.

Dutilh, G., Vandekerckhove, J., Tuerlinckx, F., and Wagenmakers, E. J. (2009). A diffusion model decomposition of the practice effect. *Psychon. Bull. Rev.* 16, 1026–1036.

Efron, B., and Tibshirani, R. J. (1986). Bootstrap methods for standard errors, confidence intervals, and other measures of statistical accuracy. *Stat. Sci.* 1, 54–77.

Efron, B., and Tibshirani, R. (1993). *An Introduction to the Bootstrap.* Boca Raton, FL: Chapman & Hall/CRC.

Faisal, A. A., Selen, L. P., and Wolpert, D. M. (2008). Noise in the nervous system. *Nat. Rev. Neurosci.* 9, 292–303.

Garrett, D. D., Kovacevic, N., McIntosh, A. R., and Grady, C. L. (2010). Blood oxygen level-dependent signal variability is more than just noise. *J. Neurosci.* 30, 4914–4921.

Garrett, D. D., Kovacevic, N., McIntosh, A. R., and Grady, C. L. (2011). The importance of being variable. *J. Neurosci.* 31, 4496–4503.

Hazlett, E. A., Dawson, M. E., Schell, A. M., and Neuchterlein, K. H. (2001). Attentional stages of information processing during a continuous performance test: a startle modification analysis. *Psychophysiology* 38, 669–677.

Honey, C. J., Kotter, R., Breakspear, M., and Sporns, O. (2007). Network structure of cerebral cortex shapes functional connectivity on multiple time scales. *Proc. Natl. Acad. Sci. U.S.A.* 104, 10240–10245.

Honey, C. J., Sporns, O., Cammoun, L., Gigandet, X., Thiran, J. P., Meuli, R., and Hagmann, P. (2009). Predicting human resting-state functional connectivity from structural connectivity. *Proc. Natl. Acad. Sci. U.S.A.* 106, 2035–2040.

Hultsch, D. F., MacDonald, S. W. S., and Dixon, R. A. (2002). Variability in reaction time performance of younger and older adults. *J. Gerontol. B. Psychol. Sci. Soc. Sci.* 57B, P101–P115.

Hultsch, D. F., MacDonald, S. W. S., Hunter, M. A., Levy-Bencheton, J., and Strauss, E. (2000). Intraindividual variability in cognitive performance in older adults: comparison of adults with mild dementia, adults with arthritis, and healthy adults. *Neuropsychology* 14, 588–598.

Hultsch, D. F., Strauss, E., Hunter, M. A., and MacDonald, S. W. S. (2008). "Intraindividual variability, cognition, and aging," in *The Handbook of Aging and Cognition (3rd edn.)*, eds F. I. M. Craik and T. A. Salthouse (New York, NY: Psychology Press), 491–556.

Jackson, J. D., Balota, D. A., Duchek, J. M., and Head, D. (2012). White matter integrity and reaction time intraindividual variability in healthy aging and early-stage Alzheimer disease. *Neuropsychologia* 50, 357–366.

Kelly, A. M. C., Uddin, L. Q., Biswal, B. B., Castellanos, F. X., and Milham, M. P. (2008). Competition between functional brain networks mediates behavioral variability. *Neuroimage* 39, 527–537.

Li, S-C., Huxhold, O., and Schmiedek, F. (2004). Aging and attenuated processing robustness: evidence from cognitive and sensorimotor functioning. *Gerontology* 50, 28–34.

Li, S-C., van Oertzen, T., and Lindenberger, U. (2006). A neurocomputational model of stochastic resonance and aging. *Neurocomputing* 69, 1553–1560.

Libera, C. D., and Chelazzi, L. (2006). Visual selective attention and the effects of monetary rewards. *Psychol. Sci.* 17, 222–227.

Lövden, M., Bäckman, L., Lindenberger, U., Schaefer, S., and Schmiedek, F. (2010). A theoretical framework for the study of adult cognitive plasticity. *Psychol. Bull.* 136, 659–676.

Lövden, M., Li, S. C., Shing, Y. L., and Lindenberger, U. (2007). Within-person trial-to-trial variability precedes and predicts cognitive decline in old and very old age: longitudinal data from the Berlin Aging Study. *Neuropsychologia* 45, 2827–2838.

MacDonald, S. W. S., Hultsch, D. F., and Bunce, D. (2006a). Intraindividual variability in vigilance performance: does degrading visual stimuli mimic age-related "Neural Noise?". *J. Clin. Exp. Neuropsychol.* 28, 655–675.

MacDonald, S. W. S., Nyberg, L., and Bäckman, L. (2006b). Intra-individual variability in behavior: links to brain structure, neurotransmission and neuronal activity. *Trends Neurosci.* 29, 474–480.

MacDonald, S. W. S., Li, S. C., and Backman, L. (2009a). Neural underpinnings of within-person variability in cognitive functioning. *Psychol. Aging* 24, 792–808.

MacDonald, S. W. S., Li, S. C., and Bäckman, L. (2009b). Neural underpinnings of within-person variability in cognitive functioning. *Psychol. Aging* 24, 792–808.

McIntosh, A. R., Kovacevic, N., and Itier, R. J. (2008). Increased brain signal variability accompanies lower behavioral variability in development. *PLoS Comput. Biol.* 4:e1000106. doi: 10.1371/journal.pcbi.1000106

McIntosh, A. R., Kovacevic, N., Lippe, S., Garrett, D. D., Grady, C. L., and Jirsa, V. (2010). The development of a noisy brain. *Arch. Ital. Biol.* 148, 323–337.

Misic, B., Vakorin, V. A., Paus, T., and McIntosh, A. R. (2011). Functional embedding predicts the variability of neural activity. *Front. Syst. Neurosci.* 5:90. doi: 10.3389/fnsys.2011.00090

Murtha, S., Cismaru, R., Waechter, R., and Chertkow, H. (2002). Increased variability accompanies frontal lobe damage in dementia. *J. Int. Neuropsychol. Soc.* 8, 360–372.

Naveh-Benjamin, M., Craik, F. I. M., Guez, J., and Kreuger, S. (2005). Divided attention in younger and older adults: effects of strategy and relatedness on memory performance and secondary task costs. *J. Exp. Psychol. Learn. Mem. Cogn.* 31, 520–537.

Rabbitt, P., Osman, P., Moore, B., and Stollery, B. (2001). There are stable individual differences in performance variability, both from moment to moment and from day to day. *Q. J. Exp. Psychol. A* 54A, 981–1003.

Ram, N., Rabbitt, P., Stollery, B., and Nesselroade, J. R. (2005). Cognitive performance inconsistency: intraindividual change and variability. *Psychol. Aging* 20, 623–633.

Ratcliff, R., Schmiedek, F., and McKoon, G. (2008). A diffusion model explanation of the worst performance rule for reaction time and IQ. *Intelligence* 36, 10–17.

Ratcliff, R., Thapar, A., and McKoon, G. (2006). Aging, practice, and perceptual tasks: a diffusion model analysis. *Psychol. Aging* 21, 353–371.

Schmiedek, F., Lövden, M., and Lindenberger, U. (2009). On the relation of mean reaction time and intraindividual reaction time variability. *Psychol. Aging* 24, 841–857.

Shammi, P., Bosman, E., and Stuss, D. T. (1998). Aging and variability in performance. *Aging Neuropsychol. Cogn.* 5, 1–13.

Shew, W. L., Yang, H., Petermann, T., Roy, R., and Plenz, D. (2009). Neuronal avalanches imply maximum dynamic range in cortical networks at criticality. *J. Neurosci.* 29, 15595–15600.

Shew, W. L., Yang, H., Yu, S., Roy, R., and Plenz, D. (2011). Information capacity and transmission are maximized in balanced cortical networks with neuronal avalanches. *J. Neurosci.* 31, 55–63.

Siegler, R. S. (1994). Cognitive variability: a key to understanding cognitive development. *Curr. Dir. Psychol. Sci.* 3, 1–5.

Spieler, D. H., Balota, D. A., and Faust, M. E. (2000). Levels of selective attention revealed through analyses of response time distributions. *J. Exp. Psychol. Hum. Percept. Perform.* 26, 506–526.

Stern, Y. (2002). What is cognitive reserve? Theory and research application of the reserve concept. *J. Int. Neuropsychol. Soc.* 8, 448–460.

Stuss, D. T., Murphy, K. J., Binns, M. A., and Alexander, M. P. (2003). Staying on the job: the frontal lobes control individual performance variability. *Brain* 126, 2363–2380.

Stuss, D. T., Pogue, J., Buckle, L., and Bondar, J. (1994). Characterization of stability of performance in patients with traumatic brain injury: variability and consistency on reaction time tests. *Neuropsychology* 8, 316–324.

Tamnes, C. K., Fjell, A. M., Westlye, L. T., Ostby, Y., and Walhovd, K. B. (2012). Becoming consistent: developmental reductions in intraindividual variability in reaction time are related to white matter integrity. *J. Neurosci.* 32, 972–982.

Tomporowski, P. D., and Tinsley, V. F. (1996). Effects of memory demand and motivation on sustained attention in young and older adults. *Am. J. Psychol.* 109, 187–204.

Tun, P. A., and Lachman, M. E. (2008). Age differences in reaction time and attention in a national telephone sample of adults: education, sex, and task complexity matter. *Dev. Psychol.* 44, 1421–1429.

Vakorin, V. A., Lippe, S., and McIntosh, A. R. (2011). Variability of brain signals processed locally transforms into higher connectivity with brain development. *J. Neurosci.* 31, 6405–6413.

West, R., Murphy, K. J., Armilio, M. L., Craik, F. I. M., and Stuss, D. T. (2002). Lapses of intention and performance variability reveal age-related increases in fluctuations of executive control. *Brain Cogn.* 49, 402–419.

Williams, B. R., Hultsch, D. F., Strauss, E. H., Hunter, M. A., and Tannock, R. (2005). Inconsistency in reaction time across the life span. *Neuropsychology* 19, 88–96.

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An investigation of response and stimulus modality transfer effects after dual-task training in younger and older

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It has been shown that dual-task training leads to significant improvement in dual-task performance in younger and older adults. However, the extent to which training benefits to untrained tasks requires further investigation. The present study assessed (a) whether dual-task training leads to cross-modality transfer in untrained tasks using new stimuli and/or motor responses modalities, (b) whether transfer effects are related to improved ability to prepare and maintain multiple task-set and/or enhanced response coordination, (c) whether there are age-related differences in transfer effects. Twenty-three younger and 23 older adults were randomly assigned to dual-task training or control conditions. All participants were assessed before and after training on three dual-task transfer conditions; (1) stimulus modality transfer (2) response modality transfer (3) stimulus and response modalities transfer task. Training group showed larger improvement than the control group in the three transfer dual-task conditions, which suggests that training leads to more than specific learning of stimuli/response associations. Attentional costs analyses showed that training led to improved dual-task cost, only in conditions that involved new stimuli or response modalities, but not both. Moreover, training did not lead to a reduced task-set cost in the transfer conditions, which suggests some limitations in transfer effects that can be expected. Overall, the present study supports the notion that cognitive plasticity for attentional control is preserved in late adulthood.

Keywords: cognitive plasticity, cognitive training, transfer, divided attention, executive function, aging

INTRODUCTION

Conversing on a cell phone while crossing the street, tuning radio channels while driving, and cooking while watching a TV program are a few activities of daily living that require dividing attention between two or more concurrent tasks at the same time. It has often been reported that aging is associated with a decline in divided attention abilities and dual-task performances (Verhaeghen and Cerella, 2002). Age-related deficits in executive control mechanisms that support dual-task abilities are a major research concern. Indeed, dual-task performances appear to be a good predictor of several negative outcomes in late life, such as falls (Verghese et al., 2002), bumping while walking (Broman et al., 2004), and car crashes (Chaparro et al., 2005; Clay et al., 2005; Kramer and Madden, 2008). Improving the ability to perform two tasks simultaneously could therefore have significant impacts in the prevention of adverse outcomes associated with aging.

It has been suggested that age-related deficits in dual-task performance can be attributed to non-executive processes such as general slowing, higher stimuli interference, and less risky strategies (Glass et al., 2000; Hein and Schubert, 2004), but a meta-analytic research that controlled for some of these confounding factors still found robust age-related deficits in dual-task performances (Verhaeghen et al., 2003). Indeed, older adults are slower and less accurate than younger adults when performing two tasks simultaneously and the age-related deficit cannot be accounted for by mere general slowing (McDowd and Shaw, 2000; Verhaeghen and Cerella, 2002; Verhaeghen et al., 2003). The age-related deficit in attention control processes that support dual-task performance have often been associated with the vulnerability of the prefrontal cortex during aging, which globally compromises executive control (Cabeza, 2001; Cabeza et al., 2004; Davis et al., 2008). Interestingly, a recent meta-analysis showed that age-related decline in executive control is not general, but seems to be specific to divided attention (Verhaeghen, 2011).

Recent studies have shown that cognitive training can help improve performances in attentional control tasks. This has been shown in switching tasks (Kray and Lindenberger, 2000; Cepeda et al., 2001; Kray and Eppinger, 2006; Kray et al., 2008; Karbach and Kray, 2009), inhibition tasks (Davidson et al., 2003; Thorell et al., 2008), and updating tasks (Dahlin et al., 2008b; Jaeggi et al., 2008). Several training studies have also demonstrated robust increase in dual-task performance after cognitive training. It has also been suggested that dual-task performance relies on at least two specific abilities: (1) the preparation and maintenance of multiple task sets, as indexed by the *task-set cost* and (2) the coordination of stimulus perception and simultaneous motor response executions, as indexed by *dual-task cost*. While training did not allow equivalent optimization in dual-task performances in older and younger adults in some studies, even after extensive training (Strobach et al., 2012), others showed equivalent improvement in task-set and dual-task costs in both older and younger adults (Kramer et al., 1995; Elke et al., 1999; Schumacher et al., 2001; Bherer et al., 2005, 2006, 2008).

Although these studies suggest that cognitive training leads to enhanced attentional control in older adults, few studies have reported convincing evidence of transfer effect after training (Dahlin et al., 2008b; Green and Bavelier, 2008; Owen et al., 2010). Transfer effects refer to the generalization of learning from the training task to an untrained task, often referred to as a transfer task. To date, little is known about the extent and limits of transfer effects after cognitive training. Among studies that used dual-task training with older adults, some studies have reported significant transfer effects (Kramer et al., 1995; Bherer et al., 2005, 2008) but others have not (Dahlin et al., 2008a; Green and Bavelier, 2008; Owen et al., 2010). Moreover, in studies that reported significant transfer effects, it remains unclear whether enhanced performance in untrained tasks were supported by an improved ability to maintain several response alternatives (reduced task-set cost) or by a better response coordination ability (reduced dual-task cost). Moreover, in some studies, transfer effects seemed larger if the untrained tasks shared strong similarity with the training task with regards to input modality (e.g., both tasks involved visual input) and motor response modality (e.g., both tasks required motor responses). The present study was conducted to assess the extent to which cross-modality transfer effects can be expected after dual-task training in older and younger adults.

According to Barnett and Ceci's (2002) taxonomy (see also Zelinski, 2009), modality transfer refers to improvement observed in a new task that involves different stimuli, or input modality, than the one that has been trained (e.g., training with a visual task leads to improvement in an auditory task). Furthermore, modality transfer can be qualified as *near* or *far* depending on the distance between the modalities of the trained task and the transfer task. *Near modality transfer* refers to improvement on novel tasks that involve new stimuli but share the same stimulus and response modalities with the training task. The notion of near modality transfer is very close to the one of within-modality transfer used in some studies (Bherer et al., 2005). For the transfer to be qualified as *far modality transfer*, training-related improvement must be observed on tasks that involve different stimulus modalities (visual to auditory) and/or response modalities (manual tapping to foot tapping) than those used in training. The notion of far modality transfer is very close to the one of cross-modality transfer used in other studies (Bherer et al., 2005). Far modality transfer appears as an essential outcome for a cognitive training program to produce significant changes in activity of daily living. For example, if transfer is specific to the trained modality, one should not aim at improving driving performance or at improving balance while talking by training on computerized software that do not involve the same input or output modalities. Moreover, knowing the extent and limits of transfer would help creating new platform, or choosing among existing ones, when it comes to use video games devices (e.g., Wii's Wii Fit™, PlayStation's Eye™, Xbox's Voice Recognition™, etc.) in the context of cognitive rehabilitation with clinical populations.

Transfer effects reported so far in dual-task training studies appear limited to *near modality transfer*, or within-modality transfer. In a recent study in older adults, half of the trained participants practiced a visual number summing task while trying to detect peripheral visuals targets (flowers), while the other half practiced a visual letter-position subtraction task while also trying to detect peripheral targets (soccer balls). Both groups showed significant improvement in untrained version of the tasks after training as opposed to control groups (Mackay-Brandt, 2011). Similarly, increased ability to maintain and prepare multiple tasks (reduced task-set cost) and enhanced coordination of the two tasks (reduced dual-task cost) were observed on transfer dual-task conditions after training (Bherer et al., 2005, 2008). These results suggest that to some extent, near modality transfer effects (or within-modality transfer effects) can be expected after dual-task training. Interestingly, younger and older adults did improve to the same extent in the transfer tasks. However, far modality transfer or cross-modality transfer, after dual-task training only received partial support so far. Bherer et al. (2005) observed that training to perform simultaneously a visual and an auditory discrimination tasks can lead to enhanced performances in an untrained dual-task condition that involved two visual tasks, although improvement in task-set cost was not significant. In a more recent study (Bherer et al., 2008), older adults trained to perform two visual tasks did show improved task-set cost, but not dual-task cost, in cross-modality transfer tasks that involved performing a visual and an auditory transfer task concurrently. Although global performances in the transfer dual-task conditions suggest that training led to a generalizable improvement in the ability to perform concurrent tasks, these results suggest that there are some limits in the amount of cross-modality (far modality) transfer effects that can be expected after dual-task training. Hence, learning to coordinate two visual tasks might generalize to untrained visual tasks, but the amount of transfer would be reduced if at least one of the untrained tasks involved the auditory modality. According to this hypothesis, a transfer dual-task condition that involved two tasks in which the modality differs from the training task should show even less transfer effects, or none at all. In a recent set of studies (Liepelt et al., 2011; Strobach et al., 2012), young students practiced a visual task (discriminating circle locations by pressing keys on the keyboard) and an auditory task (discriminating low, middle, or high tones by answering "one," "two," or "three") simultaneously. A decreased of dual-task cost was observed in transfer conditions where either the visual or the auditory task was changed from practice. However, no decreased of dual-task cost was observed in transfer condition where both tasks changed from the practiced tasks. Authors concluded that task coordination skills are non-transferable and task-specific. However, it is important to note that, a decreased of error rates was observed on the auditory transfer task which indicated some level of transfer. Moreover, for the auditory task transfer condition, tones were the same but the mapping changed to "two," "one," or "three." This likely limits the transfer effects that could be expected since participants had to inhibit the mapping learned during training. Further studies are thus required to clarify whether transfer effects can be observed after dual-task training when the transfer dual-task condition involves two new and untrained concurrent tasks.

While stimulus modality transfer effects have received some support, the extent to which cross-modality transfer effects can be expected when the response modality differs from the training to the transfer tasks has not been systematically investigated. In Voelcker-Rehage and Alberts' (2007) study, older adults were trained on a motor control task, which was paired with an untrained cognitive task before and after training. Surprisingly, participants improved on the cognitive task but did not improve on the motor task. The authors suggested that motor supervision was highly demanding before training and that there were fewer resources available for the cognitive task. So far, studies that reported transfer effects after dual-task training in older and younger adults have used the same motor response modality (keyboard input) in training than in transfer tasks. There is thus no evidence of either near or far modality transfer involving a new set of response modalities. Transfer effects to new motor responses appear particularly relevant in the context of dual-task training in older adults. Indeed, Hartley (2001) showed that age-related deficits in dual-task performances were most likely to occur if the task combination involves two motor responses. The present study assessed whether dual-task training leads to some benefits in a new dual-task combination that involved new motor response modes and if transfer effects are equivalent amount older and younger adults.

The main objective of the present study was to explore further the limits of transfer effects that can be expected after dual-task training. For the first time, cross-modality transfer effects were systematically assessed by using three dual-task conditions; a dual-task condition in which the stimuli modality differed in both tasks from the tasks used in training, a dual-task condition in which the response modality differed from the training tasks in both untrained tasks, and a third transfer condition in which both the stimuli and the output modality were new in both tasks. In all three transfer-task conditions the amount of change in task-set and dual-task costs was also measured in order to assess whether transfer effect were supported by increased preparation for multiple tasks or enhanced ability to coordinate the two concurrent tasks. Another goal of the present study was to assess whether age-related differences exist in the amount of cross-response and cross-stimulus modality transfer effects.

MATERIALS AND METHODS

PARTICIPANTS

Twenty-three older adults and 23 younger adults participated in the study. All participants were healthy community-dwellers who provided informed consent to participate in the study. The older adults group was composed of 18 women and 5 men (age: $M = 68.5 \pm 7.1$ years; education: 14.4 ± 3.4 years). The younger adults group was composed of 13 women and 10 men (age: $M = 23.7 \pm 3.0$ years; education: 15.3 ± 1.7 years). Participants were excluded if they had depressive disorder, neurological disorders, uncorrected or impaired vision or audition and a history of stroke or general anesthesia in the past 6 months. On the first session, older participants completed the Mini-Mental State Examination (Folstein et al., 1975). Participants having a score below 26/30 were excluded. Participants were then randomly assigned to training or control group. Participants were blinded to the existence of different groups. The training group was composed of 13 younger and 13 older adults while the control group was composed of 10 older and 10 younger adults.

Prior to assessment of dual-task performances, both experimental and control groups were compared through an assessment of several neuropsychological tests: verbal abstraction (Similarity test; Wechsler, 1997), verbal fluency (P-T-L phonetic fluency), mental reasoning (matrix; Wechsler, 1997), processing speed (Digit Symbol Substitution; Wechsler, 1997), short-term and working memory (Digit span forward and backward; Wechsler, 1997), and attention and executive functions (Stroop Color Test and Trail Making Test A and B (Reitan, 1958; Bohnen et al., 2002; Chatelois et al., unpublished data). For a detailed description of each test, see Lezak et al. (2004). ANOVAs performed on neuropsychological tests performances as dependent variables and training group as between group factor (training vs. control) indicated that in both younger and older adults, there was no significant difference between training and control groups (see **Table 1**).

THE DUAL-TASK PARADIGM

The dual-task paradigm runs on E-prime 2.0 from Psychology Software tools. Participants started each trial by pressing the space bar or by pressing a button on the wheel depending on the response modality. Then, a fixation point (an asterisk) appeared in the middle of the screen for 500 ms followed by stimuli presentation, which lasted until participants provided a response. Participants controlled the length of the inter-stimulus interval by triggering the next trial, but a minimum inter-stimuli interval of 750 ms was set. Participants were asked to respond as quickly and accurately as possible. A visual warning appeared when participants committed errors ("wrong answer" in red).

Each dual-task condition involved pure and mixed blocks. In pure blocks, participants performed only one of the two tasks at a time (*single-pure trials*). In mixed blocks, participants either performed the two tasks concurrently (*dual-mixed trials*) or just one of the two tasks (*single-mixed trials*). Therefore, single-mixed trials differed from dual-mixed trials simply in the presentation of one or two stimuli, with no further indication given to the participants. The order of the single- and dual-mixed trials within the mixed blocks was unpredictable. Participants were instructed to give equal priority to both tasks.

Comparisons between the different trial types provide valuable information with regard to the potential mechanisms involved in dual-task performances. Performances on single-pure trials can be viewed as an indicator of general processing speed, while comparison between single-pure and single-mixed trials (referred to as task-set cost) provides a measure of processing required to prepare and maintain multiple task sets. Difference between performances in single-mixed and dual-mixed trials can be viewed as a measure of the ability to perceive multiple stimuli and coordinate the execution of two motor responses. This measure is referred to as the dual-task cost. While a decrease of the task-set cost is interpreted as an improvement of the ability to prepare and maintain in working memory multiple stimulus–response alternatives, a decrease of the dual-task cost can be considered as an indicator of improved task coordination abilities require in executing multiple tasks.

STIMULI AND MOTOR RESPONSES

The training dual-task condition involved two visual identification tasks. Stimuli appeared in the middle of a 19″ flat screen, on

Table 1 | Demographic Data and Performance Scores on the Tests Measuring Cognitive Functions.

	Older				Younger			
	Trained (N = 13)		Control (N = 10)		Trained (N = 13)		Control (N = 10)	
	M	SD	M	SD	M	SD	M	SD
DEMOGRAPHICAL DATA								
Age(years)	68.5	6.9	68.5	7.6	24.1	3.9	23.1	2.8
Gender (# of women)	11		7		7		6	
Education (years)	14.9	1.7	13.7	4.0	14.9	1.7	15.7	1.8
IQSP	10.8	3.3	13.6	5.7	9.7	6.1	6.7	5.5
GENERAL COGNITION								
Mini Mental State Examination	28.3	1.2	28.8	0.8				
ABSTRACTION								
Similarity (WAIS-III)	24.0	4.1	24.9	4.2	27.0	3.7	24.6	3.7
Matrix (WAIS-III)	15.4	4.4	15.7	4.2	21.9	1.6	21.2	2.0
SHORT-TERM AND WORKING MEMORY								
Digit span forward	9.3	1.8	9.5	1.6	11.0	1.8	10.3	1.9
Digit span backward	6.9	2.2	7.2	3.9	7.9	1.9	7.9	2.5
PROCESSING SPEED								
Digit coding (score)	63.7	13.0	58.5	17.6	82.7	15.4	86.3	21.1
Stroop-word (ms)	42.6	5.0	43.8	5.5	37.4	6.4	40.3	4.9
Stroop-color (ms)	70.4	11.8	65.7	11.1	55.7	11.8	63.8	11.4
Trail A (ms)	37.0	10.8	41.0	14.5	23.5	7.0	27.3	7.8
VERBAL FLUENCY								
Verbal fluency P-T-L	47.5	13.3	51.3	12.6	50.9	8.8	49.3	6.6
ATTENTION AND EXECUTIVE FUNCTIONS								
Stroop-interference (ms)	120.8	23.3	113.9	21.8	87.8	15.5	92.7	18.9
Stroop-switching (ms)	137.6	29.3	137.0	30.6	107.0	21.2	115.2	30.2
Trail B (ms)	85.8	31.5	87.0	23.7	54.5	19.7	49.8	12.0

a black background. Viewing distance was approximately 45 cm. At this distance, visual stimuli subtended a vertical visual angle of 1.15° and a horizontal visual angle of 0.76°. One task required identifying the direction of a white arrow (left or right) by pressing "A" or "S" on the keyboard with the index or the middle finger of the left hand. The other task was to identify the color of a square (red or green) by pressing "K" or "L" keys with their right hand index or middle finger.

Three transfer dual-tasks conditions were designed for this study. The stimulus modality transfer (S-MT) dual-task combination involved two auditory discrimination tasks: to judge if a pure sound (990 Hz) was coming from the left or right headphone speakers and to discriminate the words "GO" or "STOP" presented in stereo in the headphone. Participants could adjust sound volume as needed and responses were provided using the same keys as in the training dual-task condition. In the response modality transfer (R-MT) condition, the participant had to turn the wheel in the direction of the arrow and had to press the accelerator or the brake depending on the color of the square, red or green. Stimuli were identical to the ones used in training dual-task condition. Finally, the stimuli–response modality transfer (SR-MT) condition used the same stimuli than the S-MT and the same responses than the R-MT.

PRE- AND POST-TRAINING PROCEDURES

In the pre- and post-training sessions, participants completed four dual-task combinations; the training task as well as the three transfer dual-task combinations. Each dual-task combination lasted around 20 min during which participants started with two pure blocks (20 single-pure trials), followed by two mixed blocks (40 single-mixed and 40 dual-mixed trials), and two pure blocks (20 single-pure trials). No feedback on speed was provided. **Table 2** resumes the blocks structure of pre and post-training evaluations.

TRAINING PROCEDURE

Less than 1 week separated training from the pre- or post-training sessions. The training regimen was composed of five training sessions of approximately 1 h each. Participants were asked to attend to two or three sessions a week but they had to wait a minimum of 1 day between each session. Training was performed in a computer room allowing 10 participants to train simultaneously. Participants from the control group did not receive the training but had to wait an equal lapse of time before being invited on the post-training evaluation.

The dual-task training condition differed from pre- and post-dual-task training conditions on several aspects. First, in each training session, participants completed two pure blocks (20 trials

Table 2 | Content (blocks and trials) of the evaluation and training sessions.

PRE- AND POST-TRAINING SESSIONS							
Overall time	80 min approx. (20 min per conditions)						
Conditions	Visual stimuli + keyboard responses, visual stimuli + wheel and brakes responses, auditory stimuli + keyboard responses, auditory stimuli + wheel and brakes responses						
	Block 1	**Block 2**	**Block 3–4**			**Block 5**	**Block 6**
Type of trials	Single-pure	Single-pure	Single-mixed	and	Dual-mixed	Single-pure	Single-pure
No of trials	20	20	40		40	20	20
Task	A	B	A or B	or	A and B	A	B
TRAINING SESSIONS							
Overall time	55 min. approx.						
Conditions	Only visual stimuli + keyboard responses						
	Block 1	**Block 2**	**Block 3–10**			**Block 11**	**Block 12**
Type of trials	Single-pure	Single-pure	Single-mixed	and	Dual-mixed	Single-pure	Single-pure
No of trials	20	20	80		80	20	20
Task	A	B	A or B	or	A and B	A	B

each) followed by eight mixed blocks (80 trials each), and two other pure blocks (20 trials each). Participants completed five training sessions, for a total of 400 single-pure trials (5 × 4 × 20), 1600 single-mixed trials (5 × 8 × 40), and 1600 dual-mixed trials (5 × 8 × 40).

Second, during training sessions a continuous, individualized adapted feedback was displayed on the computer screen. Feedback indicators were presented continuously on a histogram in the top-left portion of the screen and depicted speed performance for the dual-mixed trials. The histogram contained two bars, each one giving feedback for a specific hand. The heights indicated participants' performances (speed) in dual-mixed trials. The bars first appeared as small and red. As performances progressively got faster, the graph bars grew taller and simultaneously changed to yellow or green. The bars automatically became red when an error was made. Performances were estimated through a comparison between dual-mixed trials and single-mixed trials. The criterion for optimal performance was reached when the mean RT for the last three dual-mixed trials was smaller or equal to the median of the RT distribution for all previous single-mixed trials in a given training session.

ANALYSIS

ANOVAs were performed on RT (ms) and accuracy (% of correct responses) with Age (older vs. younger) and Group (trained vs. control) as between-subjects factors, and Session and Trial type (single-pure – single-mixed – dual-mixed) as within-subject factors. Significant interactions were decomposed with simple effects. However, in the case of a significant interaction with more than two levels of a repeated factor (e.g., Trial types), repeated contrasts were used. Such analyses provide a comparison of RT differences between two consecutive levels of a repeated factor. Statistical analyses of the data were performed on SPSS 17. An effect was reported significant according to the adjusted alpha level (Greenhouse–Geisser) when required – that is, when the Mauchly's test of sphericity was significant. Effect sizes (eta squared) are also reported. In the event of a significant effect of Age, age-related slowing was controlled for by conducting analyses of covariance (ANCOVAs) with baseline RT in the single-pure trials averaged for the two tasks of a given condition. Performances of the training group through the five training sessions will be described first. Then, performance of training and control groups will be compared from pre-test to post-test in the training dual-task condition and the three transfer dual-task conditions.

RESULTS

All participants demonstrated very high accuracy on the four dual-task combinations used at pre and post-test (training task: 98%, S-MT: 98%, R-MT: 97%, SR-MT: 97%). Variations from pre-test to post-test never exceeded 1%, which shows that accuracy remained considerably high throughout all the sessions. **Table 3** shows detailed results of the analyses on accuracy data. These results are not further described here due to absence of significant training effect or interaction. The following sections report results observed in RT data only.

TRAINING SESSIONS

An ANOVA was performed on RT with Age as between-subjects factor, and Session (1–5) and Trial type as within-subject factors. As shown in **Figure 1**, RT decreased with training, $F(4, 96) = 75.48$, $p < 0.001$, $\eta^2 = 0.76$. A Session × Trial type interaction, $F(8, 192) = 42{,}96$, $p < 0.001$, $\eta^2 = 0.64$, was also observed due to a significant decrease in task-set cost after the first, $F(1, 24) = 12.76$, $p < 0.005$, $\eta^2 = 0.35$, and the fourth session, $F(1, 24) = 4{,}50$, $p < 0.05$, $\eta^2 = 0.15$, while dual-task cost decreased after the first, $F(1, 24) = 31.37$, $p < 0.001$, $\eta^2 = 0.57$, the second, $F(1, 24) = 6.27$, $p < 0.05$, $\eta^2 = 0.20$, and the fourth sessions, $F(1, 24) = 11.39$, $p < 0.005$, $\eta^2 = 0.32$. There was also an Age × Session interaction, $F(4, 96) = 3.80$, $p < 0.01$, $\eta^2 = 0.14$. A larger improvement was observed in younger adults between session one and two, $F(1, 24) = 4{,}50$, $p < 0.005$, $\eta^2 = 0.16$. There was no age-related difference in training after session two.

Table 3 | Results of the analyses of variance performed on accuracy for the training and transfer tasks conditions used in the pre-training and post-training session.

	Training task				Transfer tasks										
	Visual-keyboard				Response-MT				Stimuli-MT			Stimuli and response-MT			
	df	*F*	*p* <	η^2	df	*F*	*p* <	η^2	*F*	*p* <	η^2	*F*	*p* <	η^2
Age (younger-older)	1.41	6.43	0.05*	0.13	1.42	1.22	n.s.	0.03	3.71	n.s.	0.08	0.13	n.s.	0.00
Group (trained-control)	1.41	2.56	n.s.	0.06	1.42	3.98	n.s.	0.08	1.32	n.s.	0.03	5.93	0.05*	0.12
Type of trial (SP, SM, DM)	2.82	49.57	0.001*	0.54	2.84	35.00	0.001*	0.46	44.73	0.001*	0.51	45.49	0.001*	0.52
Age × type	2.82	1.05	n.s.	0.02	2.84	0.13	n.s.	0.00	0.44	n.s.	0.01	0.24	n.s.	0.01
On task-set cost	1.41	0.44	n.s.	0.01	1.42	0.26	n.s.	0.00	0.70	n.s.	0.02	0.44	n.s.	0.01
On dual-task cost	1.41	0.74	n.s.	0.02	1.42	0.06	n.s.	0.00	0.23	n.s.	0.01	0.33	n.s.	0.01
Age × session	1.41	8.97	0.05*	0.18	1.42	4.08	0.05*	0.09	20.40	0.001*	0.32	2.49	n.s.	0.06
Group × session	1.41	0.65	n.s.	0.02	11.42	0.03	n.s.	0.00	5.16	0.05*	0.11	2.33	n.s.	0.05
Group × session × type of trial	2.82	3.10	n.s.	0.07	21.84	0.80	n.s.	0.02	2.44	n.s.	0.05	0.72	n.s.	0.02
On task-set cost	1.41	2.02	n.s.	0.05	11.42	0.32	n.s.	0.01	1.30	n.s.	0.03	1.08	n.s.	0.03
On dual-task cost	1.41	0.84	n.s.	0.02	11.42	0.39	n.s.	0.01	0.81	n.s.	0.02	1.19	n.s.	0.03

**p < .05*

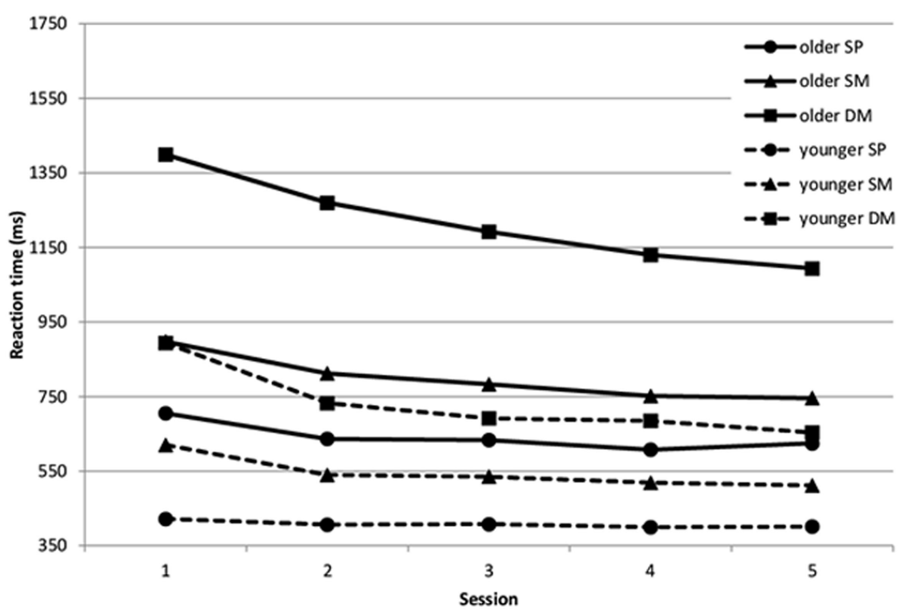

FIGURE 1 | Mean reaction time (ms) for older and younger adults in the three trial types [single pure (SP), single mixed (SM), and dual mixed (DM)], as a function training sessions.

PRE VS. POST-TRAINING SESSIONS

For each of the dual-task condition (training, S-MT, R-MT, SR-MT), an ANOVA was performed with Group (trained vs. control participants) and Age as between-subjects factors, and Session (pre and post-training) and Trial type as within-subject factors. Results are presented in **Table 4**. The main results are summarized here to address three main questions. First, did training lead to significant improvement in dual-task performances compared to the control condition? Second, is there any age-related difference in training effects? Third, did training lead to cross-modality transfer effects and if so, were transfer equivalent among older and younger adults?

First, with regards to training effect, as can be seen in **Figure 2** (top-left panel) RT improvement in training dual-task condition was larger in the training group (−326 ms) than in the control group (−169 ms), and this effect was also characterized by a Group × Session × Trial type interaction. Repeated contrasts indicated that both the task-set cost (trained: −217 ms; control: −48 ms) and the dual-task cost (trained: −356 ms; control: −97 ms) decreased

Table 4 | Results of the analyses of variance performed on reaction time for the training and transfer conditions used in the pre-training and post-training sessions.

	Training task				Transfer tasks									
	Visual-keyboard				Response-MT				Stimuli-MT			Stimuli and response-MT		
	df	*F*	*p* <	η^2	df	*F*	*p* <	η^2	*F*	*p* <	η^2	*F*	*p* <	η^2
Age (younger-older) session	1.41	80.62	0.001*	0.66	1.42	37.56	0.001*	0.47	37.52	0.001*	0.47	18.27	0.001*	0.30
Group (trained-control)	1.41	4.43	0.042*	0.10	1.42	0.08	n.s.	0.00	0.28	n.s.	0.01	0.01	n.s.*	0.00
Type of trial (SP, SM, DM)	2.82	503.52	0.001*	0.93	2.84	325.98	0.001*	0.89	601.46	0.001*	0.94	512.07	0.001*	0.92
Age × type of trial	2.82	35.43	0.001*	0.46	2.84	26.20	0.001*	0.38	13.66	0.001*	0.25	11.16	0.001*	0.21
On task-set cost	1.41	16.37	0.001*	0.29	1.42	11.75	0.001*	0.22	12.45	0.001*	0.23	8.34	0.006*	0.17
On dual-task cost	1.41	43.38	0.001*	0.51	1.42	28.35	0.001*	0.40	11.37	0.002*	0.21	9.55	0.004*	0.19
Age × session	1.41	21.30	0.001*	0.34	1.42	12.51	0.001*	0.23	2.64	0.112	0.06	4.84	0.033*	0.10
Group × session	1.41	72.84	0.001*	0.64	11.42	13.54	0.001*	0.24	17.43	0.001*	0.29	4.93	0.032*	0.16
Age × group × session	1.41	11.72	0.001*	0.22	11.41	0.64	n.s.	.0.01	2.64	n.s.	0.06	0.582	n.s.	0.01
Group × session × type of trial	2.82	37.58	0.001*	0.48	21.84	11.45	0.001*	0.21	6.71	0.001*	0.14	2.64	n.s.	0.06
On task-set cost	1.41	28.22	0.001*	0.41	1.42	2.40	n.s.	0.05	0.90	n.s.	0.02	3.39	n.s.	0.08
On dual-task cost	1.41	27.55	0.001*	0.40	1.42	14.49	0.001*	0.26	8.37	006*	17	0,88	n.s.	35

*$p < .05$

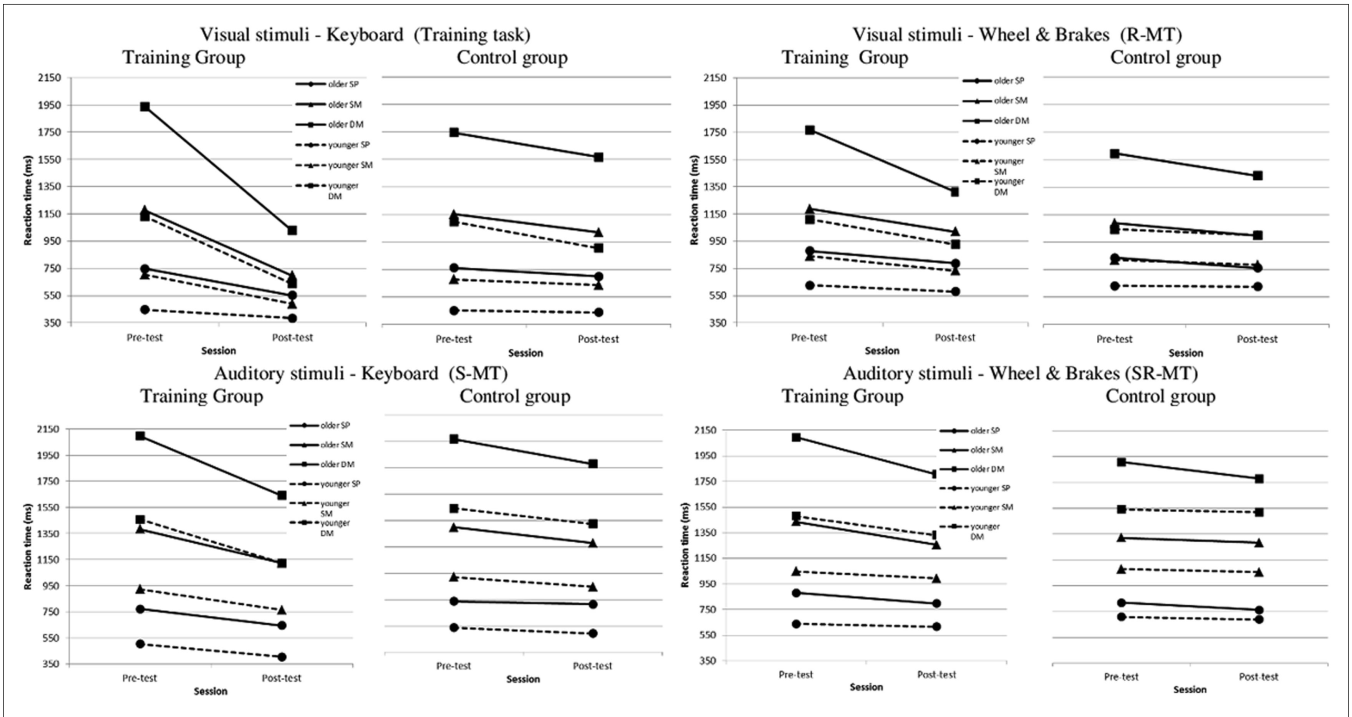

FIGURE 2 | Mean reaction time (ms) for older and younger adults in the three trial types [single pure (SP), single mixed (SM), and dual mixed (DM)], as a function of pre- and post-test sessions, for the trained dual-task condition (first panel), the response modality transfer (R-MT) dual-task condition (second panel), the stimulus modality transfer dual-task condition (S-MT) (third panel), and the stimuli–response modality transfer (RS-MT) dual-task condition (last panel).

to a greater extent in training group than in control group.

Second, an Age × Group × Session × Trial types interaction, $F(2, 82) = 6.52$, $p < 0.01$, $\eta^2 = 0.13$, was observed and the interaction remained significant after controlling for general slowing, $F(2, 80) = 6.34$, $p < 0.005$, $\eta^2 = 0.14$. Age-related differences in training were further explored by examining the Group × Session × Trial type interaction separately

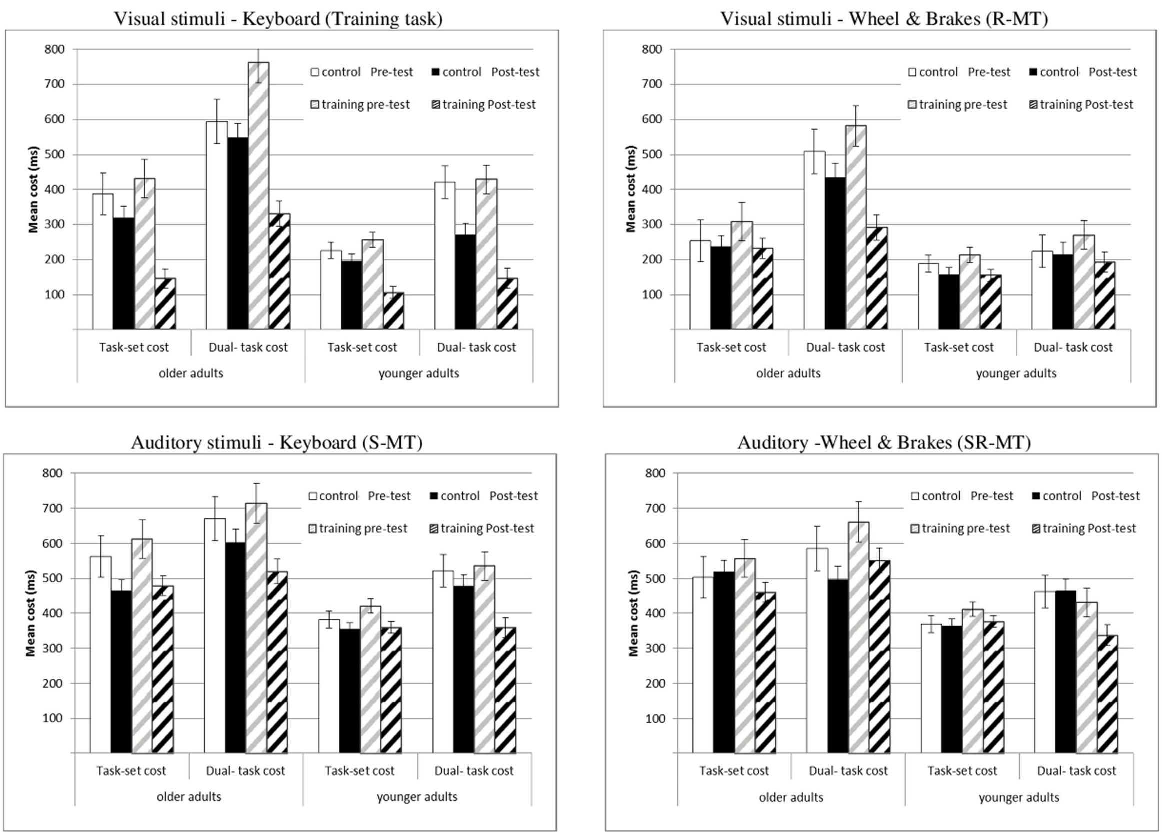

FIGURE 3 | Mean task-set cost and dual-task cost in older and younger adults at pre-test and post-test sessions, for the trained dual-task condition (first panel), the response modality transfer (R-MT) dual-task condition (second panel), the stimulus modality transfer (S-MT) dual-task condition (third panel), and the stimuli–response modality transfer (SR-MT) dual-task condition (last panel).

for younger and older adults. In older adults, a significant Group × Session × Trial type interaction was observed, $F(2, 40) = 31.29$, $p < 0.001$, $\eta^2 = 0.61$. **Figure 3** illustrates the changes in task-set and dual-task costs. Repeated contrasts showed a Group × Session interaction in task-set cost $F(1, 20) = 12.84$, $p < 0.005$, $\eta^2 = 0.39$. Simple effect analyses indicated that this interaction was due to a significant drop of task-set cost in the training group (−284 ms), $F(1, 11) = 43.81$, $p < 0.001$, $\eta^2 = 0.80$, which was not observed in the control group (−67 ms), $F(1, 9) = 2.63$, *ns*, $\eta^2 = 0.23$. A significant Group × Session interaction was also observed in dual-task cost, $F(1, 20) = 29.81$, $p < 0.001$, $\eta^2 = 0.60$. Dual-task cost decreased in the training group (−430 ms), $F(1, 11) = 106.42$, $p < 0.001$, $\eta^2 = 0.91$, but not in the control group (−45 ms), $F(1, 9) = 0.59$, *ns*, $\eta^2 = 0.06$. In younger adults, a significant Group × Session × Trial type interaction, $F(2, 42) = 8.03$, $p < 0.001$, $\eta^2 = 0.28$, was also observed. Alike older adults, repeated contrasts showed a Group × Session interaction in task-set cost, $F(1, 21) = 28.27$, $p < 0.01$, $\eta^2 = 0.57$. Simple effect analyses showed a significant drop in task-set cost in the training group (−150 ms), $F(1, 12) = 73.06$, $p < 0.001$, $\eta^2 = 0.86$, and a somewhat smaller decrease in the control group (−28 m), $F(1, 9) = 5.36$, $p < 0.05$, $\eta^2 = 0.37$. Moreover, the reduction in dual-task cost was not significantly different among trained and control participants, $F(1, 21) = 3.70$, $p = 0.068$, $\eta^2 = 0.15$. Improvement in dual-task cost was significant in both training (−282 ms), $F(1, 9) = 12.86$, $p < 0.01$, $\eta^2 = 0.59$, and control group (−149 ms), $F(1, 12) = 30.29$, $p < 0.001$, $\eta^2 = 0.72$.).

Third, regarding transfer effects, results showed an overall improvement in all three transfer dual-task conditions, as indicated by a Group × Session interaction. In all conditions, improvement was larger in training group (S-MT: −239 ms; R-MT: −175 ms; SR-MT: −122 ms) than in control group (S-MT: −93 ms; R-MT: −67 ms; SM-RT: −51 ms). However, improvement in task-set and dual-task costs depends upon transfer condition. A Group × Session × Trial type interaction was observed in the S-MT and the R-MT. Repeated contrasts showed that dual-task cost decreased more in training group (S-MT: −181 ms; R-MT: −187 ms) than in control participants (S-MT: −58 ms; R-MT: −34 ms) in both condition, but there was no group difference in change in task-set cost. In the SR-MT condition, neither task-set nor dual-task cost showed group difference in change from pre-test to post-test. Finally, the absence of Age × Group × Session or Age × Group × Session × Trial Type interaction in the three transfer dual-task combinations suggest that training-related changes in performance were equivalent among older and younger adults.

DISCUSSION

The present study assessed the limits of cross-modality transfer effects after dual-task training in older and younger adults. Participants completed 5 h of dual-task training with a dual-task combination that involved two visual discrimination tasks and both tasks were answered manually through keyboard keys. The main objectives of the present study were to determine (a) if far modality transfer effects occur on tasks with untrained stimuli and/or motor responses modalities, (b) if transfer effects are due to specific improvements on task-set cost or dual-task cost, (c) if there are age-related differences in dual-task transfer effects. Participants were assessed before and after training on several dual-task conditions; (1) auditory stimuli and keyboard responses (S-MT), (2) visual stimuli and wheel and brakes responses (R-MT), (3) auditory stimuli and wheel and brake responses (SR-MT).

As expected, the training effectiveness was confirmed as both younger and older adults showed improved performance after training, but training effects differed among age groups. In older adults, the training group showed improved task-set and dual-task costs compared to controls, while in younger adults, only task-set cost showed significant improvement. In younger adults, both training and control groups showed improved dual-task cost. This suggests that in younger adults' minimal exposition to the dual-task condition (test–retest effect) leads to significant improvement in task coordination. Overall, these results on training effects are highly consistent with previous findings using the same training paradigm (Bherer et al., 2005, 2008).

The specific contribution of the present study was to test the limits of modality transfer effects induced by dual-task training. Results of the present study indicated that participants that completed the training showed larger improvement in all three transfer-task combinations compared to control participants. Therefore, results support the existence of far modality transfer effects since training led to significant improvements in conditions in which both input and output modalities changed from training to transfer tasks conditions. Moreover, training led to significant improvements in dual-task cost in both S-MT and R-MT. These findings are of major importance since they demonstrate that training effects can be observed after dual-task training despite the fact that stimuli or motor response modalities differed from training. This suggests that training leads to greater learning than a specific stimuli/response association and that this learning can be generalized to new situations. However, since task-set cost did not decrease after training, it is unlikely that the improvement observed in the S-MT and R-MT dual-task conditions arose from better preparation of stimulus–response mapping or from a decrease of the task load on working memory. The present results thus suggest that transfer effects are supported by an improvement in executive control required to coordinate two concurrent tasks. However, the results observed in the SR-MT dual-task conditions brought limited support to this conclusion. In fact, in this condition, attentional costs did not improve, which suggests that performance improvement was merely supported by a general improvement in processing speed.

Liepelt et al. (2011) and Strobach et al. (2011) observed transfer in novel tasks of the same modalities and concluded that transfer in dual-task was relatively robust. In line with this, results of the present study suggest that training did improve a set of skills that are independent of the specific modality characteristics of the training program. However, past studies did not assess transfer effect when both input and output modalities differ from training. Results of the present study suggest that transfer effects can be limited when both stimuli and response modalities differed from the training conditions.

The improvement observed here in a dual-task condition that involved visual stimuli or motor responses has strong theoretical and practical implications. In fact, it has been reported that age-related dual-task deficits are larger when both tasks involve a visual input and a similar motor outputs (Hartley, 2001; Hein and Schubert, 2004). The present findings suggest that after dual-task training participants tend to overcome input and output interference, which leads to better coordination of two concurrent tasks and that this improvement is equivalent among younger and older adults. With regards to potential application in the context of cognitive rehabilitation, results of the present study suggest that a patient trained on a visual balance multitask would also improve on an auditory balance multitasks. This supports the uses of computerized software and videogames devices in modalities that are not exactly the same as the activities of daily living that they aimed to improve.

The present findings also suggest that there are some limits in the extent to which transfer occurs after dual-task training. When both input stimuli and response mode changed in the SR-MT condition, improvements of task-set cost and dual-task cost were equivalent among training and control groups, despite a larger gain overall in the training group. This suggests that transfer may be limited to an increase of general speed when the transfer condition shares neither stimuli nor motor response modality with the training dual-task condition. Together with the results observed in the S-MT and R-MT dual-task conditions, these results suggest that learning to coordinate two concurrent tasks is relatively modality specific and would not lead to improvement in coordinating sets of new stimuli with new responses modality. It thus seems that the general improvement observed in the SR-MT condition may, in fact, be caused by a familiarization toward the dual-task environment. It may also be that only the training group was exposed to a feedback on speed, which would have led to enhanced motivation to provided faster responses with training.

With regard to potential age-related differences in transfer effects, results of the present study suggest quite consistently age-equivalent generalizable gains. Among all the three transfer dual-task combinations, transfer effects were equivalent between older and younger participants. These results bring further support to the notion that cognitive plasticity is preserved in advance age (Verhaeghen, 2000; Basak et al., 2008). Improvements induced by cognitive training, as observed in the present study, can be attributed to cognitive plasticity. In fact, neural correlates of dual-task performance improvement have been observed in studies using a dual-task paradigm very similar to the one used in the present study (Erickson et al., 2005, 2007). According to Lovden et al. (2010), two phenomena can induce improvement of performance after training: *flexibility* which denotes the capacity to optimize the brain's performance within the limits of the current state of functional supply and *plasticity* which denotes the acquisition of new knowledge and change of the current state of functional supply. Future studies would be require to specify whether transfer effects observed in the present study are due to improved flexibility (e.g., better coordination strategies) or neural plasticity (wider or more efficient neuronal recruitment).

The present study has some limits. In order to consolidate present findings, one should verify that the patterns of effects observed here are not specific to the training protocol that was used. For example, it would be interesting to examine if training with auditory stimuli and verbal responses induces transfer effects in dual-task condition that combines visual stimuli and manual responses. Future studies should also assess the maintenance of transfer effects by re-evaluating subjects after a few months. Finally, more attention should be given to training components that enhance transfer. For example, varying task priorities and individualizing feedback might be among the determining components that support transfer.

Little is known about the extent and limits of transfer effects following cognitive training. The present study innovates by supporting far transfer modality to untrained stimuli and untrained response modalities. While a few studies have investigated transfer to untrained stimulus modality, none had systematically examined transfer to untrained motor responses. In the present study, transfer effects were notably large even though the training lasted only 5 h distributed on 2–3 weeks. Considering the growing interest in cognitive interventions that include dual-task training in order to preserve older adults gait and balance (Li et al., 2010), as well as driving abilities (Cassavaugh and Kramer, 2009), it appears important to identify the mechanisms by which transfer effects occur and to better understand the extent and limits of transfer effects that can be expected after dual-task training. Such knowledge could support development of new training paradigms that target real-life situations.

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REFERENCES

Barnett, S. M., and Ceci, S. J. (2002). When and where do we apply what we learn? A taxonomy for far transfer. *Psychol. Bull.* 128, 612–637.

Basak, C., Boot, W. R., Voss, M. W., and Kramer, A. F. (2008). Can training in a real-time strategy video game attenuate cognitive decline in older adults? *Psychol. Aging* 23, 765–777.

Bherer, L., Kramer, A. F., Peterson, M. S., Colcombe, S., Erickson, K., and Becic, E. (2005). Training effects on dual-task performance: are there age-related differences in plasticity of attentional control? *Psychol. Aging* 20, 695–709.

Bherer, L., Kramer, A. F., Peterson, M. S., Colcombe, S., Erickson, K., and Becic, E. (2006). Testing the limits of cognitive plasticity in older adults: application to attentional control. *Acta Psychol. (Amst.)* 123, 261–278.

Bherer, L., Kramer, A. F., Peterson, M. S., Colcombe, S., Erickson, K., and Becic, E. (2008). Transfer effects in task-set cost and dual-task cost after dual-task training in older and younger adults: further evidence for cognitive plasticity in attentional control in late adulthood. *Exp. Aging Res.* 34, 188–219.

Bohnen, N., Jolles, J., and Twijnstra, A. (2002). Neuropsychological deficits in patients with persistent symptoms six months after mild head injury. *Neurosurgery* 30, 692–695; discussion 695–696.

Broman, A. T., West, S. K., Munoz, B., Bandeen-Roche, K., Rubin, G. S., and Turano, K. A. (2004). Divided visual attention as a predictor of bumping while walking: the Salisbury Eye Evaluation. *Invest. Ophthalmol. Vis. Sci.* 45, 2955–2960.

Cabeza, R. (2001). Cognitive neuroscience of aging: contributions of functional neuroimaging. *Scand. J. Psychol.* 42, 277–286.

Cabeza, R., Daselaar, S. M., Dolcos, F., Prince, S. E., Budde, M., and Nyberg, L. (2004). Task-independent and task-specific age effects on brain activity during working memory, visual attention and episodic retrieval. *Cereb. Cortex* 14, 364–375.

Cassavaugh, N. D., and Kramer, A. F. (2009). Transfer of computer-based training to simulated driving in older adults. *Appl. Ergon.* 40, 943–952.

Cepeda, N. J., Kramer, A. F., and Gonzalez de Sather, J. C. (2001). Changes in executive control across the life span: examination of task-switching performance. *Dev. Psychol.* 37, 715–730.

Chaparro, A., Wood, J. M., and Carberry, T. (2005). Effects of age and auditory and visual dual tasks on closed-road driving performance. *Optom. Vis. Sci.* 82, 747–754.

Clay, O. J., Wadley, V. G., Edwards, J. D., Roth, D. L., Roenker, D. L., and Ball, K. K. (2005). Cumulative meta-analysis of the relationship between useful field of view and driving performance in older adults: current and future implications. *Optom. Vis. Sci.* 82, 724–731.

Dahlin, E., Neely, A. S., Larsson, A., Backman, L., and Nyberg, L. (2008a). Transfer of learning after updating training mediated by the striatum. *Science* 320, 1510–1512.

Dahlin, E., Nyberg, L., Backman, L., and Neely, A. S. (2008b). Plasticity of executive functioning in young and older adults: immediate training gains, transfer, and long-term maintenance. *Psychol. Aging* 23, 720–730.

Davidson, D. J., Zacks, R. T., and Williams, C. C. (2003). Stroop interference, practice, and aging. *Neuropsychol. Dev. Cogn. B Aging Neuropsychol. Cogn.* 10, 85–98.

Davis, S. W., Dennis, N. A., Daselaar, S. M., Fleck, M. S., and Cabeza, R. (2008). Que PASA? The posterior-anterior shift in aging. *Cereb. Cortex* 18, 1201–1209.

Elke, K., Begerow, J., Oppermann, H., Kramer, U., Jermann, E., and Dunemann, L. (1999). Determination of selected microbial volatile organic compounds by diffusive sampling and dual-column capillary GC-FID – a new feasible approach for the detection of an exposure to indoor mould fungi? *J. Environ. Monit.* 1, 445–452.

Erickson, K. I., Colcombe, S. J., Wadhwa, R., Bherer, L., Peterson, M. S., Scalf, P. E., and Kramer, A. F. (2005). Neural correlates of dual-task performance after minimizing task-preparation. *Neuroimage* 28, 967–979.

Erickson, K. I., Colcombe, S. J., Wadhwa, R., Bherer, L., Peterson, M. S., Scalf, P. E., and Kramer, A. F. (2007). Training-induced functional activation changes in dual-task processing: an fMRI study. *Cereb. Cortex* 17, 192–204.

Folstein, M. F., Folstein, S. E., and McHugh, P. R. (1975). "Mini-mental state." A practical method for grading the cognitive state of patients for the clinician. *J. Psychiatr. Res.* 12, 189–198.

Glass, J. M., Schumacher, E. H., Lauber, E. J., Zurbriggen, E. L., Gmeindl, L., Kieras, D. E., and Meyer, D. E. (2000). Aging and the psychological refractory period: task-coordination strategies in young and old adults. *Psychol. Aging* 15, 571–595.

Green, C. S., and Bavelier, D. (2008). Exercising your brain: a review of human brain plasticity and training-induced learning. *Psychol. Aging* 23, 692–701.

Hartley, A. A. (2001). Age differences in dual-task interference are localized to response-generation processes. *Psychol. Aging* 16, 47–54.

Hein, G., and Schubert, T. (2004). Aging and input processing in dual-task situations. *Psychol. Aging* 19, 416–432.

Jaeggi, S. M., Buschkuehl, M., Jonides, J., and Perrig, W. J. (2008). Improving fluid intelligence with training on working memory. *Proc. Natl. Acad. Sci. U.S.A.* 105, 6829–6833.

Karbach, J., and Kray, J. (2009). How useful is executive control training? Age differences in near and far transfer of task-switching training. *Dev. Sci.* 12, 978–990.

Kramer, A. F., Larish, J., and Strayer, D. L. (1995). Training for attentional control in a dual task setting: a comparison of young and old adults. *J. Exp. Psychol. Appl.* 1, 50–76.

Kramer, A. F., and Madden, D. J. (2008). "Attention," in *The Handbook of Aging and Cognition*, 3rd Edn, eds F. I. M. Craik and T. A. Salthouse (New York: Psychology Press), 189–250.

Kray, J., Eber, J., and Karbach, J. (2008). Verbal self-instructions in task switching: a compensatory tool for action-control deficits in childhood and old age? *Dev. Sci.* 11, 223–236.

Kray, J., and Eppinger, B. (2006). Effects of associative learning on age differences in task-set switching. *Acta Psychol. (Amst.)* 123, 187–203.

Kray, J., and Lindenberger, U. (2000). Adult age differences in task switching. *Psychol. Aging* 15, 126–147.

Lezak, M. D., Howieson, D. B., and Loring, D. W. (2004). *Neuropsychological Assessment*, 4th Edn. New York: Oxford University Press.

Li, K. Z., Roudaia, E., Lussier, M., Bherer, L., Leroux, A., and McKinley, P. A. (2010). Benefits of cognitive dual-task training on balance performance in healthy older adults. *J. Gerontol. A Biol. Sci. Med. Sci.* 65A, 1344–1352.

Liepelt, R., Strobach, T., Frensch, P., and Schubert, T. (2011). Improved intertask coordination after extensive dual-task practice. *Q. J. Exp. Psychol. (Hove)* 64, 1251–1272.

Lovden, M., Backman, L., Lindenberger, U., Schaefer, S., and Schmiedek, F. (2010). A theoretical framework for the study of adult cognitive plasticity. *Psychol. Bull.* 136, 659–676.

Mackay-Brandt, A. (2011). Training attentional control in older adults. *Neuropsychol. Dev. Cogn. B. Aging Neuropsychol. Cogn.* 18, 432–451.

McDowd, J. M., and Shaw, R. L. (2000). "Attention and aging: a functional perspective," in *The Handbook of Aging and Cognition*, eds F. I. M. Craik and T. A. Salthouse (Mahwah: Erlbaum), 221–292.

Owen, A. M., Hampshire, A., Grahn, J. A., Stenton, R., Dajani, S., Burns, A. S., and Ballard, C. G. (2010). Putting brain training to the test. *Nature* 465, 775–778.

Reitan, R. M. (1958). Validity of the trail making test as an indicator of organic brain damage. *Percept. Mot. Skills* 8, 271–276.

Schumacher, E. H., Seymour, T. L., Glass, J. M., Fencsik, D. E., Lauber, E. J., Kieras, D. E., and Meyer, D. E. (2001). Virtually perfect time sharing in dual-task performance: uncorking the central cognitive bottleneck. *Psychol. Sci.* 12, 101–108.

Strobach, T., Frensch, P. A., Soutschek, A., and Schubert, T. (2011). Investigation on the improvement and transfer of dual-task coordination skills. *Psychol. Res.* (in press).

Strobach, T., Liepelt, R., Schubert, T., and Kiesel, A. (2012). Task switching: effects of practice on switch and mixing costs. *Psychol. Res.* 76, 74–83.

Thorell, L. B., Lindqvist, S., Nutley, S. B., Bohlin, G., and Klingberg, T. (2008). Training and transfer effects of executive functions in preschool children. *Dev. Sci.* 12, 106–113.

Verghese, J., Buschke, H., Viola, L., Katz, M., Hall, C., Kuslansky, G., and Lipton, R. (2002). Validity of divided attention tasks in predicting falls in older individuals: a preliminary study. *J. Am. Geriatr. Soc.* 50, 1572–1576.

Verhaeghen, P. (2000). "The interplay of growth and decline. Theoretical and empirical aspects of plasticity of intellectual and memory performance in normal old age," in *Cognitive Rehabilitation in Old Age*, eds R. D. Hill, L. Bäckman, and A. S. Neely (New York: Oxford University Press), 3–22.

Verhaeghen, P. (2011). Aging and executive control: reports of a demise greatly exaggerated. *Curr. Dir. Psychol. Sci.* 20, 174–180.

Verhaeghen, P., and Cerella, J. (2002). Aging, executive control, and attention: a review of meta-analyses. *Neurosci. Biobehav. Rev.* 26, 849–857.

Verhaeghen, P., Steitz, D. W., Sliwinski, M. J., and Cerella, J. (2003). Aging and dual-task performance: a meta-analysis. *Psychol. Aging* 18, 443–460.

Voelcker-Rehage, C., and Alberts, J. L. (2007). Effect of motor practice on dual-task performance in older adults. *J. Gerontol. B. Psychol. Sci. Soc. Sci.* 62, P141–P148.

Wechsler, D. (1997). *Wechsler Adult Intelligence Scale-Third Edition: Administration and Scoring Manual.* San Antonio: The Psychological Corporation.

Zelinski, E. M. (2009). Far transfer in cognitive training of older adults. *Restor. Neurol. Neurosci.* 27, 455–471.

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Testing the limits of optimizing dual-task performance in younger and older adults

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Impaired dual-task performance in younger and older adults can be improved with practice. Optimal conditions even allow for a (near) elimination of this impairment in younger adults. However, it is unknown whether such (near) elimination is the limit of performance improvements in older adults. The present study tests this limit in older adults under conditions of (a) a high amount of dual-task training and (b) training with simplified component tasks in dual-task situations. The data showed that a high amount of dual-task training in older adults provided no evidence for an improvement of dual-task performance to the optimal dual-task performance level achieved by younger adults. However, training with simplified component tasks in dual-task situations exclusively in older adults provided a similar level of optimal dual-task performance in both age groups. Therefore through applying a testing the limits approach, we demonstrated that older adults improved dual-task performance to the same level as younger adults at the end of training under very specific conditions.

Keywords: cognitive aging, dual-task performance, testing the limits, practice

INTRODUCTION

In recent years, a number of studies have examined the effect of practice on dual-task performance across different age groups in order to better understand the basic cognitive mechanisms underlying dual-task performance and cognitive aging (Maquestiaux et al., 2004, 2010; Bherer et al., 2005, 2006, 2008; Göthe et al., 2007; Allen et al., 2009; Hartley et al., 2011). In younger adults, some studies have even demonstrated perfect time sharing of two tasks after practice defined by zero performance costs in dual compared to single-tasks (i.e., dual-task costs; Van Selst et al., 1999; Ruthruff et al., 2001, 2003; Schumacher et al., 2001). However, such findings of perfect or near perfect time sharing are lacking in the aging literature on older adults. The aim of the present study was to close this gap. Therefore, we investigated the limits of dual-task performance optimization in older adults (i.e., near perfect or perfect time sharing) and, furthermore, tested the conditions of such optimization.

Investigations of (near) perfect time sharing with practice are interesting for aging research because they may provide more conclusive evidence about cognitive plasticity, its range, and developmental mechanisms in older adults (Bherer et al., 2006). In particular, testing the limits of optimizing dual-task performance in older adults should demonstrate, in the case of complex task situations, the maximum cognitive performance potential or the "latent" reserve capacity of older adults in a more appropriate way than investigating cognitive abilities of older people without extensive practice. Baltes, Lindenberger and colleagues (e.g., Lindenberger et al., 1992; Lindenberger and Baltes, 1995) have argued that the testing the limits approach can lead to an identification of true age-related cognitive decline, rather than overestimate age-related differences due to non-optimized testing conditions, assuming that age-related differences in reserve capacity are more accurately assessed near the limits of performance. Rephrased in the testing the limits terminology, we test the *developmental reserve* when assessing the limits of optimized dual-task performance in older adults. This test is essential because older adults' difficulty in performing concurrent tasks is one of the most well documented executive control deficits in cognitive aging literature (e.g., Allen et al., 1998; Hartley and Little, 1999; Glass et al., 2000; McDowd and Shaw, 2000; Hartley, 2001; Verhaeghen et al., 2003; Hein and Schubert, 2004; Verhaeghen, 2011). This deficit may result from age-impaired attentional control processes that are related to the substantial modifications observed in the frontal and prefrontal areas of the cerebral cortex during aging (e.g., West, 1996; Raz, 2000).

OPTIMIZING DUAL-TASK PERFORMANCE IN YOUNGER AND OLDER ADULTS

Meyer and Kieras (1999) outlined conditions for optimal dual-task performance. In particular, the authors listed five prerequisites, which should be fulfilled in order to achieve such performance: "(Condition 1) participants are encouraged to give the tasks equal priority; (Condition 2) participants are expected to perform each task quickly; (Condition 3) there are no constraints on temporal relations or serial order among responses; (Condition 4) different tasks use different perceptual and motor processors; and (Condition 5) participants receive enough practice to compile complete production rule sets for performing each task" (p. 54).

Previous attempts to compare practice-related improvements in older and younger adults' dual-task processing have provided impressive findings concerning cognitive plasticity in old age; however, unfortunately, they have not yet considered all of the conditions mentioned above and consequently their findings may not be fully conclusive regarding the limits of practice-related changes in older adults' dual-task performance. For instance, Maquestiaux et al. (2010) applied a dual-task practice situation that emphasizes response speed for and extensive practice of only one component task (i.e., Conditions 1, 3, and 5 of Meyer and Kieras, 1999, were not implemented). In a different line of research, Bherer et al. (2005, 2006) did not include all conditions when applying similar perceptual and motor processors on the component tasks (i.e., Condition 4 was not implemented).

One such situation including conditions for optimal dual-task performance was applied in younger and older adults by Strobach et al. (2012b), see also Schumacher et al., 2001). The authors asked participants to perform a training paradigm that consisted of tasks with different perception and motor components (Condition 4): a visual-manual (i.e., the visual task) and an auditory-vocal choice RT task (i.e., the auditory task). During training with these tasks (Condition 5), three different trial types were performed: participants performed only one of the two tasks in single-task blocks (single-task trials); in mixed blocks, participants either responded to only one task (i.e., mixed single-task trials) or actually executed two motor responses to simultaneously presented stimuli in two different tasks (dual-task trials with stimulus onset asynchrony, SOA, of 0 ms). Participants were instructed to respond as quickly and as accurately as possible with equal priority and with no prespecified serial order to both stimuli in these trials (Conditions 1, 2, and 3). They received adaptive and continuous on-screen feedback as well as performance-based monetary bonuses for optimized RT and error performance.

The training RTs in single-task, mixed single-tasks, and dual-task trials up to Session 8 (younger adults) and Session 12 (older adults) are summarized in **Figure 1** and **Tables 1** and **2**. Dual-task costs are illustrated by the mean difference of dual-task and mixed single-task trials. At the end of eight training sessions, these dual-task costs were extremely reduced in younger adults (see also Schumacher et al., 2001; Hazeltine et al., 2002; Tombu and Jolicoeur, 2004; Strobach et al., 2008; Liepelt et al., 2011; Strobach et al., in press; for an adaption to a task switching situation see Strobach et al., 2012a). These findings demonstrate that in dual-task situations, implementing the prerequisite conditions for optimal dual-task performance (Meyer and Kieras, 1999), younger adults show nearly eliminated dual-task costs, i.e., near perfect time sharing, at the end of training; for the reasons for the not perfect but near perfect time sharing in this design see "General Discussion." In older adults, however, dual-task costs were still relatively high after the same amount of training (i.e., eight sessions) and even after four additional training sessions when compared to the reduced costs in younger adults. Thus, these data provide no evidence for near perfect time sharing in older adults when testing the limits of cognitive functioning in this age group (e.g., Baltes and Kliegl, 1992).

However, it is conceivable that the defined conditions of Meyer and Kieras (1999) enable near perfect time sharing in younger and older adults. However, these conditions were not appropriately set to the requirements of older adults' cognitive processing and learning functions in Strobach et al. (2012b). Consequently, the aim of the present paper is to modulate task and training characteristics in the dual-tasks of Strobach et al. to create conditions for near perfect time sharing in older adults. In fact, we modulated two crucial factors of this dual-task training procedure: (1) we increased the amount of training (Experiment 1) and (2) we simplified the included component tasks (Experiment 2).

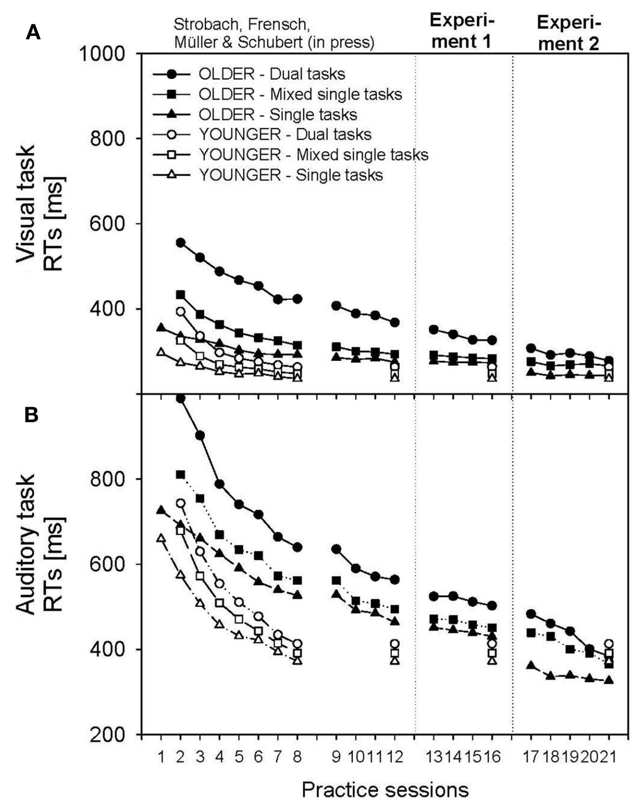

FIGURE 1 | Mean reaction times (RTs) in milliseconds (ms) on single-task trials in single-task blocks, single-task trials in mixed blocks (mixed single-task trials), and dual-task trials for (A) the visual task and (B) the auditory task across Sessions 2–21 (older adults) or Sessions 2–8 (younger adults). Session 2–12: Strobach et al. (2012b), Session 13–16: Experiment 1, Session 17–21: Experiment 2.

EXPERIMENT 1

One potential explanation for the difference in the dual-task costs between younger and older adults at the end of practice could be the different initial costs in both age groups (e.g., also see Allen et al., 2009). The reduction of these higher costs in older adults to the level of reduced costs in younger adults may require an increased amount of practice in the former group. For instance, this requirement may result from the older adults' slower speed in automatizing task sets during practice (e.g., Kramer et al., 1995). Thus, one possible method to optimize the level of dual-task performance in older adults is to increase the amount of training in this group of participants. This increase in the amount of training is similar to a strategy applied by Maquestiaux et al. (2008) in younger adults. Participants in that study conducted an increased amount of task training compared to a previous study by Ruthruff et al. (2006) to provide optimal conditions for eliminating dual-task performance costs. After this increase, a larger proportion of younger adults performed dual-tasks at an optimized level.

Table 1 | Error rates in percent in single-task trials of single-task blocks, single-task trials in mixed blocks (mixed single-task trials), and dual-task trials for the visual task in older and younger adults across Sessions 2–12 (older adults) or Sessions 2–8 (younger adults).

Task	Session	Older adults			Younger adults		
		Single-task trials	Mixed single-task trials	Dual-task trials	Single-task trials	Mixed single-task trials	Dual-task trials
Visual task	2	1.8	0.4	2.3	2.3	0.4	3.9
	3	1.4	1.0	3.1	3.0	1.0	2.2
	4	1.6	0.7	2.7	3.9	1.5	2.1
	5	1.8	0.5	2.2	4.0	1.3	1.9
	6	2.0	1.5	2.6	4.7	1.3	1.8
	7	2.0	1.0	1.5	5.7	2.3	2.5
	8	2.4	0.8	1.3	4.9	1.9	2.6
	9	2.1	1.3	1.4			
	10	3.1	1.2	0.8			
	11	3.2	1.3	0.8			
	12	3.3	1.5	0.6			
	13	3.7	1.8	0.8			
	14	3.2	2.3	1.2			
	15	3.8	1.6	1.2			
	16	3.6	2.9	1.3			
	17	1.9	2.4	2.9			
	18	3.6	3.9	0.5			
	19	0.8	0.5	1.4			
	20	1.1	1.4	1.2			
	21	1.9	0.4	1.1			

Session 2–12: Strobach et al. (2012b), Session 13–16: Experiment 1, Session 17–21.

Findings also exist about the effects of an increased training amount on dual-task performance through our study with older adults (Strobach et al., 2012b) demonstrating that such increase leads to improved dual-task performance even with prior training, i.e., after four additional sessions following eight prior training sessions.

In fact, in Experiment 1, we increased the amount of dual-task training by adding four sessions immediately after the end of the 12 sessions with the identical older adults of Strobach et al. (2012b). Such a prolongation of training with an identical group of participants makes a novel contribution of the present experiment by testing whether prolonged practice after 12 training sessions enabled older adults to arrive at a performance limit (i.e., near perfect time sharing). This prolongation is plausible because dual-task performance improved until Session 12 and the limit was not attained in this session. Note that we refer to the additional sessions in the following sections of Experiment 1 as Session 13–16 as these sessions immediately followed the Sessions 1–12 reported in Strobach et al. The performance after combined training of 16 sessions with these older adults were compared with the optimized dual-task "*target*" performance, i.e., reduced dual-task costs reflecting near perfect time sharing, in younger adults after the eighth training session. In this way, we doubled the amount of training in older compared to younger adults before we assessed dual-task performance. If this doubling produces conditions for near perfect time sharing in older adults, we would expect the same level of dual-task performance, i.e., (extremely) reduced dual-task costs, at the end of training in younger adults (i.e., Session 8) and older adults (i.e., Session 16). However, if such doubling is not sufficient to produce conditions for near perfect time sharing in older adults, dual-task costs should not be (extremely) reduced in this age group and should increase the amount of younger adults' costs.

METHOD

Participants

Ten older adults (mean age = 63.3 years, SD = 3.4, range 57–68, 5 female) were recruited from university courses for senior adults at LMU Munich. Alternatively, the 10 younger adults (mean age = 22.7 years, SD = 3.3, range 19–29, 5 female) were recruited from the university's bachelor and diploma courses. Older and younger adults were paid eight Euros per session plus performance-based monetary bonuses for their participation (for bonus details see Procedure and Design). All participants were generally well educated, with older adults reporting more years of education ($M = 18.0$ years, SD = 3.9 years) than younger adults ($M = 14.2$ years, SD = 1.4 years), $t(18) = 2.962$, $p < 0.01$; this higher number years of education in older adults may follow from the prerequisite condition of university courses for senior adults of a prior, completed study. On a five-point health rating scale (1 = poor health; 5 = *excellent health*), older and younger adults gave similar mean self-ratings of 4.4 (SD = 0.7) and 3.7 (SD = 1.3), respectively, $t(18) = 1.544$, $p = 0.14$. Participants were screened for normal or corrected to normal vision and hearing via self-report. Older adults also had no history of neurological diseases, diabetes or coronary disease, and did not take any medication that might have affected cognition. The Mini-Mental State

Table 2 | Error rates in percent in single-task trials of single-task blocks, single-task trials in mixed blocks (mixed single-task trials), and dual-task trials for the auditory task in older and younger adults across Session 2–21 (older adults) or Session 2–8 (younger adults).

Task	Session	Older adults			Younger adults		
		Single-task trials	Mixed single-task trials	Dual-task trials	Single-task trials	Mixed single-task trials	Dual-task trials
Auditory task	2	10.7	13.5	16.6	4.1	3.7	6.3
	3	11.5	11.4	12.3	3.3	3.4	5.8
	4	8.4	9.0	12.0	1.9	3.0	3.9
	5	6.6	7.6	10.6	3.1	2.4	5.4
	6	9.3	6.9	9.8	6.1	4.5	5.7
	7	6.0	7.9	9.2	5.1	4.5	5.8
	8	7.0	5.8	7.3	3.9	3.5	5.6
	9	6.7	6.7	9.8			
	10	7.8	7.0	10.0			
	11	8.2	6.8	8.7			
	12	8.2	6.8	9.2			
	13	6.6	5.5	8.3			
	14	7.2	8.8	9.7			
	15	6.9	7.1	9.8			
	16	9.4	8.7	10.0			
	17	1.1	1.2	1.5			
	18	1.1	3.3	1.7			
	19	1.1	0.9	1.3			
	20	1.8	4.3	3.0			
	21	2.7	2.5	4.1			

Session 2–12: Strobach et al. (2012b), Session 13–16: Experiment 1, Session 17–21: Experiment 2.

Table 3 | Age, formal education, general health status, attention performance, non-verbal intelligence, and vocabulary knowledge for older and younger adults; MMSE (mini-mental state examination) scores for older adults only; CFT 20-R, cultural fair intelligence test, WST, Wortschatztest (vocabulary test).

	Older adults, $N = 10$ ($N = 8$)			Younger adults, $N = 10$		
	M	**SD**	**Range**	***M***	**SD**	**Range**
Age (in years)	63.6 (63.3)	3.4 (3.8)	57–68 (57–68)	22.7	3.3	19–29
Education (in years)	18.0 (17.2)	3.9 (3.9)	13–24 (13–24)	14.2**	1.4	13–16.5
Health status (1–5)	4.4 (4.5)	0.7 (0.8)	3–5 (3–5)	3.7 ns	1.3	1–5
Attention and concentration performance (d2 Test) overall performance	410.9 (400.0)	90.6 (96.3)	284–559 (299–559)	532.9**	80.0	410–632
Concentration performance	144.5 (139.0)	46.3 (50.0)	62–212 (62–212)	204.1**	66.1	94–279
Intelligence test (CFT 20-R) IQ	96.4 (96.3)	18.0 (20.4)	76–134 (76–134)	114.2*	15.4	80–142
Vocabulary test (WST) IQ	114.2 (113.8)	8.6 (8.4)	97–125 (97–125)	107.3 ns	8.0	92–118
MMSE (maximum score = 30)	29.8 (29.7)	0.4 (0.5)	29–30 (29–30)			

$^{**}p < 0.01$, $^{*}p < 0.05$, ns, non-significant.

Examination (MMSE; Folstein et al., 1975) indicated no impaired cognitive abilities among the older participants ($M = 29.8$, $SD = 0.4$, range = 29–30). A handedness test (Oldfield, 1971) indicated that participants in both groups were right-handed.

In order to further characterize the participants, we conducted paper-and-pencil tests on attention performance (d2 Test; Brickenkamp and Zillmer, 1998), a non-verbal intelligence test [Culture Fair Intelligence Test (CFT 20-R); Weiß, 2006], and a vocabulary test [Wortschatztest (WST); Anger et al., 1968]. As illustrated in **Table 3**, performance in the d2 Test in the overall and concentration scores was higher in younger adults compared with older adults, $t(18) = 3.192$, $p < 0.01$ and $t(18) = 2.335$, $p < 0.05$, respectively. Similarly, non-verbal intelligence was optimized in younger adults in contrast with older adults, $t(18) = 2.373$, $p < 0.05$. The vocabulary test indicated similar vocabulary knowledge in both groups of participants, $t(18) = 1.864$, $p > 0.08$; such findings demonstrate the typical finding of impaired fluid processing functions but robust crystallized knowledge across aging (e.g., Cavanaugh and Blanchard-Fields, 2006).

Apparatus and stimuli

Stimuli were presented on a 17″ color monitor that was connected to a Pentium 1 PC. Experiments were carried out using ERTS software (*Experimental Runtime System*; Beringer, 2000).

A visual and an auditory task were performed. In the visual task, a circle appeared in one of three possible locations on the screen (left, middle, or right). Participants responded manually, indicating the location of the circle with the corresponding index, middle or ring finger of the right hand. The circles were white and were horizontally arranged on a black background on the computer screen. Each circle subtended approximately 2.5 cm which corresponds to a 2.38° visual angle, from a viewing distance of 60 cm. Three horizontal white lines served as placeholders at the possible left, middle, and right locations of the screen. The distance between the circles was 1 cm, which corresponded to approximately 0.95°. All circles subtended approximately 8.99°. Responses were recorded with a response board connected to the computer.

On the auditory task, participants verbally responded to one of three possible sine wave tones played on headphones with a sound level of 75 dB. They responded by saying “ONE” to the low frequency tone (350 Hz), “TWO” to the middle frequency tone (900 Hz) or “THREE” to the high frequency tone (1,650 Hz; German: “EINS,” “ZWEI,” and “DREI”). Verbal reactions were recorded with a Sony microphone connected to a voice key.

Procedure and design

A single-task trial started with three white lines serving as placeholders signaling the beginning of a trial for 500 ms. After this period had elapsed, an additional circle appeared in the visual task and remained visible until the participant responded or until a maximum of 2,000 ms had elapsed. A tone lasting for 40 ms was played in the auditory task. In dual-task trials, a circle and a tone were presented simultaneously. RTs were given as feedback after each trial for 1,500 ms followed by a blank screen for 700 ms. In dual-task trials, only the faster of the two RTs was given as feedback at the end of the trial to minimize the load. When participants committed an error or 2,000 ms had elapsed, the RT feedback was replaced by the German word for error (“Fehler”) for the same amount of time.

There were two types of blocks: single-task blocks and mixed blocks. In the single-task blocks, participants performed either 45 single-task trials of the visual task or of the auditory task. During mixed blocks, participants performed a mixture of 30 single-task trials (mixed single-task trials), 15 of the visual task and 15 of the auditory task, and 18 dual-task trials. All trials were randomly intermixed, requiring participants to switch between processing different single-task and dual-task trials. Participants were instructed to respond to both stimuli as quickly and accurately as possible during all blocks, to give these their full concentration and to give both tasks equal priority.

In order to familiarize the participants with the characteristics of the visual and auditory task and so that these could learn these tasks before presenting dual-task trials, participants exclusively performed six visual and six auditory single-task blocks in Session 1; these blocks were presented in an alternating order. Session 2 included six single-task blocks (three visual and three auditory single-task blocks) and eight mixed blocks. After two initial single-task blocks (one visual and one auditory single-task block), sequences of two mixed blocks and one single-task block followed in this session. The design in Sessions 3–16 was identical to that in Session 2 but these sessions included two additional mixed blocks at the end. In the Sessions 2–16, half of the participants always started with a visual single-task block and the other half always with an auditory single-task block; subsequently, the type of single-task block (i.e., visual or auditory) alternated. While Session 1 lasted around 45 min the following sessions took about 60 min. Sessions were conducted on successive days (excluding weekends). In this way, all sessions were completed within 2 weeks.

To maximize participants’ motivation for achieving fast performance, reward was given in the form of a monetary performance-based payoff (see also Schumacher et al., 2001; Tombu and Jolicoeur, 2004). The payoff matrix was based on an adaptive comparison between participant’s RT in a current block and a reference RT; this reference RT represents the individual best mean block RT and is adjusted separately for the visual and the auditory task and for task conditions (single-task trials in single-task blocks vs. dual-task trials). Participants could earn the more money the nearer the current RTs were to the reference RTs or if current block RTs were faster than the reference RTs; in the latter case reference RTs were adjusted to current block RTs. Bonus payments were also made on the basis of accuracy rates: A bonus was given for each correct response while there was a deduction from this bonus for each incorrect response.

RESULTS

RT analyses

For the analysis of the training effects in the older adults, we compared the data of the final training session before the present training phase started (i.e., Session 12 of Strobach et al., 2012b) with the final session in the present training phase (i.e., Session 16). Therefore, we conducted 2 × 3 mixed measures ANOVAs with the within-subject factors SESSION (Session 12 vs. 16) and TRIALTYPE (single-task trials, mixed single-task trials, and dual-task trials) separately for each component task. Following the RT training data, we analyzed the performance in older adults’ Session 16 and younger adults’ Session 8. Our primary indicator of dual-task performance was the RT difference between dual-task trials and mixed single-task trials that reflects dual-task costs. In addition, we report the difference between mixed single-task trials and single-task trials that reflects task-set costs; this measure demonstrates the requirement to prepare for and maintain multiple task sets in mixed single-task conditions as compared with the condition of single-task blocks (Rogers and Monsell, 1995; Kray and Lindenberger, 2000; Bherer et al., 2005).

During older adults’ training, RTs in the *visual task* declined considerably, $F(1, 9) = 11.041$, $p < 0.01$, partial $\eta_p^2 = 0.55$. In addition, RTs differed between trial types, $F(2, 18) = 19.420$, $p < 0.001$, partial $\eta_p^2 = 0.68$, indicating higher RTs in dual-task trials followed by mixed single-task trials and single-task trials (dual-task vs. mixed single-task trials and mixed single-task trials vs. single-task trials: all ps < 0.05). TRIALTYPE was qualified by an interaction with SESSION, $F(2, 18) = 10.310$, $p < 0.001$, partial $\eta_p^2 = 0.53$. A decomposition of this interaction into comparisons of mixed single-task trials vs. dual-task trials and single-task trials vs. mixed single-task trials in Session 12 and 16 showed that dual-task costs, $F(1, 9) = 9.558$, $p < 0.05$, partial $\eta_p^2 = 0.52$, and task-set costs, $F(1, 9) = 9.292$, $p < 0.05$, partial $\eta_p^2 = 0.51$, decreased during training (**Figure 1**). The comparison of the dual-task performance of younger adults in Session 8 and this performance of older adults in Session 16 showed larger dual-task costs in the latter group [older adults: 43 ms, $t(9) = 3.484$, $p < 0.01$; younger adults: 15 ms, $t(9) = 3.815$, $p < 0.01$; between group comparison: $F(1, 18) = 8.022$, $p < 0.01$, partial $\eta_p^2 = 0.31$] while task-set costs showed no statistical group difference [older adults: 10 ms, $t(9) = 3.550$, $p < 0.01$; younger adults: 12 ms, $t(9) = 2.955$, $p < 0.05$; between group comparison: $F(1, 18) < 1$] as illustrated in **Figure 2**.

In the *auditory task*, RTs were slower in Session 12 than in Session 16, $F(1, 9) = 33.333$, $p < 0.001$, partial $\eta_p^2 = 0.79$. Also, RTs were slower in dual-task trials than in mixed single-task trials ($p < 0.001$) followed (by trend) in single-task trials ($p < 0.077$), $F(2, 18) = 17.457$, $p < 0.001$, partial $\eta_p^2 = 0.66$. A non-significant interaction of SESSION and TRIALTYPE, $F(6, 54) = 1.897$, $p > 0.179$, partial $\eta_p^2 = 0.17$, indicated similar training effects on all types of trials. Similar to the visual task, we found increased dual-task costs in older adults' Session 16 when contrasted with these costs of younger adults in Session 8 [older adults: 57 ms, $t(9) = 4.889$, $p < 0.001$; younger adults: 22 ms, $t(9) = 4.787$, $p < 0.001$; between group comparison: $F(1, 18) = 8.022$, $p < 0.01$, partial $\eta_p^2 = 0.31$] while task-set costs showed no group difference [older adults: 20 ms, $t(9) = 1.935$, $p > 0.08$; younger adults: 20 ms, $t(9) = 3.529$, $p < 0.01$; between group comparison: $F(1, 18) < 1$] as illustrated in **Figure 2**.

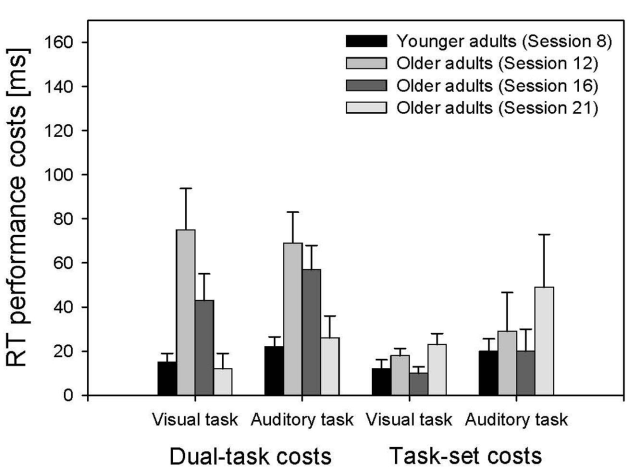

FIGURE 2 | Dual-task and task-set costs in younger adults (Session 8) and older adults (Session 12, 16, 21) in RTs. Session 8 and 12: Strobach et al. (2012b), Session 16: Experiment 1, Session 21: Experiment 2.

In the preceding analyses we used a strong and reliable criterion for measuring dual-task performance, by assessing dual-task costs in the RT comparison of dual-task trials and mixed single-task trials (i.e., dual-task costs = dual-task RTs − mixed single-task RTs; Bherer et al., 2006; Hazeltine et al., 2002). However, this criterion may lead to interpretative difficulties if there were baseline differences in performance due to the general slowing of processing in older adults (Somberg and Salthouse, 1982; Guttentag, 1989; Riby et al., 2004); in fact, this might have obscured possible differences between younger adults' dual-task performance in Session 8 and older adults' dual-task performance in Session 16 in the visual and auditory RT data. Therefore, we additionally assessed dual-task performance in terms of *proportional dual-task costs* to control for baseline differences between the age groups: proportional dual-task costs = (dual-task RTs − mixed single-task RTs)/mixed single-task RTs (Riby et al., 2004). The analyses of proportional dual-task costs corroborated the findings in the analyses of dual-task costs: Older adults showed larger proportional dual-task costs in the visual task, $t(18) = 2.174$, $p < 0.05$, and the auditory task, $t(18) = 2.429$, $p < 0.05$, than younger adults at the end of training. Thus, the appearance of dual-task cost differences between both aging groups is not confounded by possible differences in single-task performance between groups; therefore a general slowing in older adults cannot explain the observed differences in dual-task costs of Session 16 (older adults) and Session 8 (younger adults; Verhaeghen et al., 2003).

In addition, we analyzed whether the mean dual-task advantage in younger adults compared with older adults also holds at an individual level of data analysis (Schumacher et al., 2001; Hartley et al., 2011). For this purpose, we plotted the dual-task costs of the visual and the auditory task for each individual older and younger adult in Session 8 and 16, respectively (**Figure 3**). In this Brinley plot, data points for individual participants with lower costs in both tasks are located in the lower left corner while participants with larger costs are located in the upper right corner. Data points for younger adults are mostly in the lower left corner that represents relatively low dual-task costs of both tasks in Session 8. Data points of most individual older adults are at positions that represent larger costs and impaired dual-task performance relative to younger adults. Only some older adults showed data at a performance level approaching that of the younger adults. Thus, the observed difference in mean dual-task costs between the age groups at the end of training, therefore largely holds at an individual level.

Summarizing the RT data, older adults showed a benefit of training on dual-task and task-set costs from Session 12 to 16 in the visual task, but not in the auditory task. Important for the present question of near perfect time sharing, dual-task costs in older adults were still increased after doubling the number of their training sessions compared to younger adults. Task-set costs were similar across both age groups.

Error analyses

Similar to the training RT data, error rates in Session 12–16 were analyzed for single-task, mixed single-task, and dual-task trials

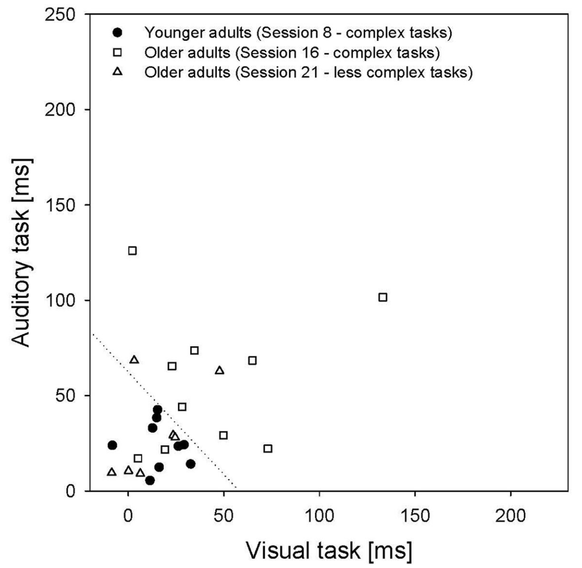

FIGURE 3 | Individual dual-task reaction time (RT) costs in younger and older adults at the end of practice (i.e., younger adults: Session 8, older adults: Session 16, 21). The *x*-axis represents the costs in the visual task while the *y*-axis represents the costs in the auditory task.

in older adults. In the *visual task*, there were lower error rates in dual-task than in mixed single-task, and in single-task trials, $F(2, 18) = 9.509$, $p < 0.01$, partial $\eta_p^2 = 0.51$ (dual-task vs. mixed single-task trials and mixed single-task trials vs. single-task trials: all $ps < 0.05$; **Table 1**). The effect of SESSION were marginally significant, $F(1, 9) = 5.102$, $p = 0.05$, partial $\eta_p^2 = 0.36$, revealing increased error rates in Session 16 than in Session 12. The interaction of both factors was non-significant, $F(2, 18) = 1.274$, $p > 0.31$, partial $\eta_p^2 = 0.12$. The findings of increased single-task error rates and increased error rates at the end of training are consistent with previous findings in younger adults using a similar task situation (Schumacher et al., 2001; Hazeltine et al., 2002; Tombu and Jolicoeur, 2004; Liepelt et al., 2011; Strobach et al., in press) and may be explained by a reduced degree of attentiveness in the visual task due to reduced processing demands. The analysis of older adults' error rates during training revealed no effects or interaction in the *auditory task* (**Table 2**).

DISCUSSION

In Experiment 1, we tested whether an increased amount of dual-task training in older adults (i.e., 16 sessions) improved dual-task performance in these learners to a level of near perfect time sharing in younger adults with only eight training sessions. The analyses of mean RT data revealed that older adults still show increased dual-task costs. Thus, this group did not optimize dual-task performance to a level achieved by younger adults. This difference even remained after we controlled for baseline differences in processing speed (i.e., proportional dual-task costs; e.g., Riby et al., 2004). Observations on a participant level demonstrated that most individual older adults performed on a lower dual-task level than the individuals of the younger adult group.

Could it be that older adults simply need even more training sessions to arrive at the same level of dual-task performance as younger adults? Generally, there is no way to rule out this conjecture; for any finite amount of training given to older adults, the possibility remains that more training would eventually eliminate dual-task cost differences between groups. However, we believe that moderately more training for older adults would not have changed the results concerning the level of dual-task performance because training had no RT effect on the dual-task costs of the visual and the auditory task, $Fs(1, 9) < 1$, across the last two training sessions. That is, the dual-task costs of the older adults were not further reduced at the end of training in Experiment 1.

Alternative to an increased amount of training, older adults may achieve the level of near perfect time sharing of younger adults due to training with component tasks that are simpler when compared to the tasks applied in Experiment 1. We tested this assumption in the following Experiment 2.

EXPERIMENT 2

A number of dual-task studies reported that simplified component tasks lead to a reduced impairment of one or both tasks in dual-task situations and, therefore, a reduction of dual-task costs (e.g., Frith and Done, 1986; Pashler, 1994; Van Selst and Jolicoeur, 1997; Schubert, 1999, 2008). This was particularly demonstrated for practiced dual-task performance in older adults (Maquestiaux et al., 2004).

One way to simplify tasks and, as a result, optimize dual-task performance/reduce dual-task costs is to reduce the number of stimulus-response mappings in the component tasks when contrasted with more difficult tasks. There exist two sources to explain reduced dual-task costs in situations with tasks that include a reduced number of stimulus-response mappings. First, the number of these mappings particularly affects the processing time of a central response selection stage (e.g., Schubert, 1999). When the processing time of the response selection stage is shortened, the likelihood of an overlap of the potential capacity-limited bottleneck stages in two concurrent tasks is reduced; in this way, the interference between concurrently presented tasks and the resulting dual-task costs are reduced. An additional source to explain reduced dual-task costs with tasks including a reduced number of stimulus-response mappings is associated with task coordination processes (Logan and Gordon, 2001). For instance, such processes perform a switch between capacity-limited central stages in a first task and in a second executed task (Maquestiaux et al., 2004; Sigman and Dehaene, 2006; Liepelt et al., 2011). Operations carried out during these processes potentially include activating or instantiating the stimulus-response mapping rules of the second task. To do so, it may be that the rules must be reactivated in or moved back into working-memory. The important point is that this switching stage functions more efficiently with a reduced amount of information handled in the case of simpler component tasks. This efficient functioning may result in faster switching between tasks and in a reduction of dual-task costs; previous findings of Maquestiaux et al. (2004) are consistent with this assumption. Taken together, we hypothesize that the reduction of the number of mapping rules may lead to shortened bottleneck stages within the component tasks and/or facilitate a switching process in older adults which may lead to reduced age differences in dual-task performance.

To investigate the effects after dual-task training with simplified component tasks, the older adults of Experiment 1 continued training after changing from three-choice to two-choice versions of the visual and the auditory tasks. In these two-choice versions, the visual task exclusively included presentations of circles at a left or a right position while low and high tones were exclusively presented in the auditory task. These tasks were trained for five sessions; note that we refer to these sessions in the following sections of Experiment 2 as Sessions 17–21, as older adults continued this training after the end of training in Session 1–16 (Strobach et al., 2012b; the present Experiment 1). The performance in the older adults' Session 21 was compared with performance of near perfect time sharing in younger adults after eight training sessions. If training with simplified tasks produces conditions for near perfect time sharing in older adults, we expect the same level of dual-task performance across the included age groups, i.e., similarly reduced dual-task costs in younger and older adults. However, if training with such simplified tasks is not sufficient to produce conditions for near perfect time sharing in older adults, dual-task costs should not be reduced in this age group and should increase the amount of younger adults' costs in Session 8.

METHOD

Participants

The groups of older and younger participants were identical to Experiment 1 with the exception that two older adults (one female, one male) were not available for further training sessions. As illustrated in **Table 3**, age, formal education, general health status, attention and concentration performance, non-verbal intelligence, vocabulary knowledge, and MMSE scores for the remaining older adults (in brackets) were similar to these data in Experiment 1. In addition, for the data in Session 16, we found similar dual-task RT and error costs in the older adults included into Experiment 2 when compared to that group of older adults in Experiment 1, $Fs(1, 16) < 1$. So, participants in Experiment 2 are highly representative for the group of older adults in Experiment 1.

Apparatus, stimuli, procedure, and design in Session 17–21 were identical to Experiment 1 with the following exceptions. In the visual task, circles exclusively appeared at the left or the right location on the screen while participants responded to one of only two possible tones, the low frequency and the high frequency tones. Single-task blocks included 46 single-task trials while mixed blocks included 52 trials (20 dual-task trials, 16 visual single-task trials, 16 auditory single-task trials); the trial number in single-task and mixed blocks was varied after Experiment 1 to fit the requirement of a similar proportion of single and dual-task trials with three-choice and two-choice tasks across Experiment 1 and 2, respectively.

RESULTS

The data handling for statistical analysis was similar to Experiment 1.

RT analyses

In older adults, training RTs in the *visual task* differed between trial types, $F(1, 7) = 19.152$, $p < 0.001$, partial $\eta_p^2 = 0.73$, indicating higher RTs in dual-task trials followed by mixed single-task trials, and single-task trials (dual-task vs. mixed single-task trials and mixed single-task trials vs. single-task trials: all $ps < 0.01$). The effect of SESSION, $F(1, 7) = 46.555$, $p < 0.001$, partial $\eta_p^2 = 0.87$, revealing faster RTs in Session 21 than in Session 16, was modulated by TRIALTYPE, $F(2, 14) = 4.313$, $p < 0.05$, partial $\eta_p^2 = 0.38$. A decomposition of this modulation into comparisons of mixed single-task trials vs. dual-task trials and single-task trials vs. mixed single-task trials in Session 16 and 21 demonstrated that dual-task costs, $F(1, 7) = 7.896$, $p < 0.05$, partial $\eta_p^2 = 0.53$, decreased and task-set costs, $F(1, 7) = 14.785$, $p < 0.01$, partial $\eta_p^2 = 0.70$, increased during training (**Figure 1**). Importantly, the comparison of the dual-task performance of younger adults in Session 8 and this performance in older adults in Session 21 revealed no difference in dual-task costs [older adults: 12 ms, $t(7) = 1.831$, $p > 0.10$; younger adults: 15 ms, $t(9) = 3.815$, $p < 0.01$; between group comparison: $F(1, 16) < 1$] as well as in proportional dual-task costs, $t(16) < 1$. Further, there was no statistical group difference in the task-set costs [older adults: 23 ms, $t(7) = 4.489$, $p < 0.05$; younger adults: 12 ms, $t(9) = 2.955$, $p < 0.05$; between group comparison: $F(1, 18) = 2.851$, $p > 0.11$] as illustrated in **Figure 2**.

The *auditory task* RT data showed faster responses in Session 21 than in Session 16, $F(1, 7) = 18.079$, $p < 0.01$, partial $\eta_p^2 = 0.72$. Also, RTs were faster in single-task, than in mixed single-task, and in dual-task trials, $F(2, 14) = 15.754$, $p < 0.001$, partial $\eta_p^2 = 0.69$ (dual-task vs. mixed single-task trials and mixed single-task trials vs. single-task trials: all $ps < 0.05$). TRIALTYPE was qualified by an interaction with SESSION, $F(2, 14) = 6.271$, $p < 0.05$, partial $\eta_p^2 = 0.47$. As illustrated in **Figure 1**, the magnitude of dual-task costs decreased, $F(1, 7) = 4.810$, $p < 0.05$, partial $\eta_p^2 = 0.42$, while task-set costs increased from Session 16 to 21, $F(1, 7) = 21.642$, $p < 0.01$, partial $\eta_p^2 = 0.76$; these latter findings parallel the progression of these costs in the visual task. Also similar to the visual task, we found no difference between the dual-task costs in the older adults' Session 21 and younger adults' Session 8 [older adults: 26 ms, $t(7) = 2.610$, $p < 0.05$; younger adults: 22 ms, $t(9) = 4.787$, $p < 0.001$; between group comparison: $F(1, 16) < 1$] as well as no difference in the proportional dual-task costs, $t(16) = 1.941$, $p > 0.09$. Task-set costs were increased in older when compared to younger adults in these sessions [older adults: 49 ms, $t(7) = 4.667$, $p < 0.01$; younger adults: 20 ms, $t(9) = 3.529$, $p < 0.01$; between group comparison: $F(1, 18) = 6.981$, $p < 0.05$, partial $\eta_p^2 = 0.30$] as illustrated in **Figure 2**; the latter may result from an increased training benefit of single-task compared with mixed single-task trials in older adults.

Illustrations of individual dual-task costs in the visual and auditory task revealed that after additional training with simplified tasks, most of the older adults reached the dual-task performance level of younger adults in Session 8 (**Figure 3**).

Summarizing the RT data, older adults showed a training effect on dual-task and task-set costs in both tasks. Most important for the question about limits of dual-task performance in older adults, we showed similarly reduced dual-task costs, i.e., near perfect time sharing, in older and younger adults at the end of training (i.e., Session 21 in older adults vs. Session 8 in younger adults).

Error analyses

In the training data of the *visual task* (**Table 1**), TRIALTYPE was significant, $F(2, 14) = 3.962$, $p < 0.05$, partial $\eta_p^2 = 0.36$, demonstrating lower error rates in dual-task than in single-task trials ($p < 0.05$); this dual-task advantage in the error rates of the visual task is well-known from previous studies (e.g., Hazeltine et al., 2002; Strobach et al., in press) and the present Experiment 1. There was no effect of, or interaction with SESSION. The analysis of error rates in the *auditory task* revealed no effects or interaction (**Table 2**).

DISCUSSION

The findings of the visual and the auditory task demonstrate near perfect time sharing at the end of training in older adults (Session 21) and younger adults (Session 8). In fact, absolute and proportional dual-task costs were similar in both groups. Note that this similar cost level was only achieved with additional training and simpler component tasks in older adults relative to younger adults. The analysis of individual dual-task costs largely confirmed the analysis at the group level.

The dual-task performance of older adults in Session 21 represented the first session, in which these participants showed the same optimized dual-task "target" performance for both tasks that younger adults showed at the end of their training. In fact, absolute dual-task costs in the visual task were similar in older and younger adults already prior to Session 21 (i.e., Session 17–20), $ts(16) < 2.052$, $ps > 0.06$, but they were larger for older adults in the auditory task in all prior sessions, $ts(16) > 2.289$, $ps < 0.05$. Thus, the combination of the training Sessions 17–21 and reduced task complexity (after the completion of prior 16 sessions with more complex tasks) is essential for optimized dual-task performance in older adults.

GENERAL DISCUSSION

The aim of the present study was to test the limits of optimized dual-task performance in older adults (i.e., Baltes and Kliegl, 1992) through the application of appropriate conditions for such optimization. Based on a dual-task situation including conditions for near perfect time sharing in younger adults (Schumacher et al., 2001; Strobach et al., 2012b), we tested whether an increased amount of training in this situation and/or training in this situation with simplified component tasks represent such conditions for older adults.

A basic finding of the present study is that older adults demonstrated improved dual-task performance with practice; this improvement parallels findings of a number of previous dual-task practice studies in this age group (e.g., Maquestiaux et al., 2004; Allen et al., 2009; Hartley et al., 2011). A novel finding of the present study is, however, that older adults even improve dual-task performance after extensive prior training over 12 sessions. This finding shows the substantial plasticity in cognitive functioning in this age group (Kramer and Willis, 2003) on the one hand; on the other hand, one may suggest that the implementation of this plasticity requires a large amount of practice.

Concerning our primary focus on the limits of dual-task optimization in older adults, our results show that an increased amount of training in older compared with younger adults does not result in optimized dual-task performance. That is, the dual-task costs of older adults were increased compared to these costs in younger adults in Experiment 1. However, after training with simpler component tasks in older adults, we observed similar levels of dual-task performance across different age groups. These similar levels in younger and older adults are indicated by similar dual-task costs in Session 21 (older adults) and Session 8 (younger adults) of Experiment 2. In this way, older adults as well as younger adults achieved near perfect time sharing[1].

However, the achievement of similar dual-task performance levels in older adults, compared with younger adults, occurs exclusively under very specific conditions. First, we tested dual-task performance under conditions that were defined as optimal for younger adults (e.g., Meyer and Kieras, 1999); these findings are reported in Strobach et al. (2012b). Second, we doubled the amount of training of older compared to younger adults under these optimal dual-task conditions. Third, we continued to adapt these conditions to the requirements of older adults through the introduction of simpler component tasks in this age group. The dual-task performance in older adults exclusively adjusted to near perfect time sharing under the latter condition.

From a different perspective, one may critically argue that these specific conditions of testing older adults' dual-task performance were unfair when faced with the test conditions in younger adults. We do not disagree with this argument. However, investigating the effects of training on dual-task performance under identical conditions was not the critical issue of the present study. Instead, we aimed to achieve near perfect time sharing in older adults (i.e., the developmental reserve). Testing the developmental reserve under identical conditions in younger and older adults was the aim of Bherer et al. (2006). Similar to the findings of Strobach et al. (2012b), these authors demonstrated similar effects across an identical amount of training in these age groups. Bherer et al. (2005, 2006) as well as Strobach et al. demonstrated still increased dual-task performance costs at the end of this training in older compared with younger adults. These findings were consistent although both lines of studies (i.e., Bherer and colleagues/Strobach

[1]An increased amount of education in older compared with younger adults (see **Table 3**) had no impact on the between group comparisons (i.e., older vs. younger adults) of dual-task and task-set costs at the end of training in Experiment 1 and 2. These comparisons were similar in analyses of the visual and auditory task when *years of education* were introduced as a covariate into the mixed measures ANOVAs including the factors SESSION, AGE GROUP, and TRIALTYPE (dual-task costs: dual-task trials vs. mixed single-task trials; task-set costs: mixed single-task trials vs. single-task trials) and with no covariate inclusion into such analyses (see Results). This finding is consistent with a comparison between older and younger adults at the end of the same amount of training in both age groups (i.e., Session 8, Strobach et al., 2012b). Furthermore, impacts of fatigue and/or training did not obscure the between group comparisons of dual-task and task-set costs within Session 16 (Experiment 1) and 21 (Experiment 2). This was demonstrated by non-significant effects or interactions of the additional factor PHASE (first session half vs. second session half) in mixed measures ANOVAs including the factors AGE GROUP and TRIALTYPE (dual-task costs: dual-task trials vs. mixed single-task trials; task-set costs: mixed single-task trials vs. single-task trials) on the visual and auditory task data in Session 16 and 21.

and colleagues) applied component tasks with different levels of complexity (two-choice vs. three-choice RT tasks) and different output-modality combinations (two manual tasks vs. one manual/one vocal task).

However, training with one manual and one vocal task exclusively under a two-choice condition (with extensive prior training with three-choice tasks) enables near perfect time sharing in older adults, as illustrated in the present Experiment 2. Based on the present training design, we cannot conclusively disentangle whether the critical factor for such performance is the extensive prior training (reported in Strobach et al., 2012b, plus the present Experiment 1) and/or the introduction of simplified tasks. We assume however that extensive training does not explain near perfect time sharing exclusively and task simplification is the major factor leading to this performance level. This assumption is supported by our observation of no further training benefit at the end of 16 sessions with the three-choice RT tasks (see Discussion of Experiment 1) but a continuation of this benefit with two-choice RT tasks in the subsequent sessions. The exclusive impact of prior training on near perfect time sharing in the present Experiment 2 is further weakened by the findings of Maquestiaux et al. (2004) demonstrating a reduced training benefit in older adults with complex tasks and a following impressive drop of dual-task costs (in their case the psychological refractory period effect; Pashler, 1994) in older compared with younger adults after the introduction of simplified component tasks. (Unfortunately, there was no subsequent training in the dual-task situation with the simplified tasks to test its training effect and to provide conclusions about the impact of prior training and task simplification on near perfect time sharing in Maquestiaux et al.) Potentially, the introduction of two-choice RT tasks allows for a continuation of the dual-task performance improvement to the level of near perfect time sharing because both of these simpler tasks could be efficiently activated in working-memory, while this task activation is not efficient with more complex tasks (i.e., three-choice RT tasks). Such non-efficient activation may result from impaired working-memory functions particularly present in older adults (Hartley and Little, 1999; Maquestiaux et al., 2004). Due to the equal priority instructions on both tasks of our dual-task situation as well as feedback and monetary bonuses in all sessions, there was no assessment of the testing the limits parameters *baseline* (i.e., standard conditions) and *baseline reserve* (i.e., optimized standard conditions due to, for instance, motivation). Therefore, there are no conclusions regarding these parameters from the present study in comparison to their outcomes in Bherer et al. (2006).

In a recent study, Hartley et al. (2011) provided evidence that some older adults showed performance consistent with perfect time sharing and did so with relatively little training. However, "compared to the central processes required in the conventional dual-task procedure, this (i.e., Hartley et al.'s) procedure reduced the demands of stimulus categorization" (p.186) by perfect redundancy between the stimuli of two tasks in dual-task situation (e.g., a left circle in a visual task was always combined with a low tone in an auditory task). Therefore, we assume no performance of two completely unrelated component tasks in the dual-task situation of Hartley and colleagues. Consequently, we present the first study in the aging literature that achieved optimized performance (i.e., near perfect time sharing) in a "conventional" dual-task situation.

However, we demonstrated findings of near perfect time in a dual-task situation that showed even zero dual-task costs (i.e., perfect time sharing) in a similar dual-task situation. That is, at the end of training, RT differences between dual-task and single-task trials were greatly reduced, but residual dual-task costs remained even in younger adults. This suggests that findings of a complete dual-task cost reduction are not easily obtained as a result of dual-task training (Schumacher et al., 2001), which is in line with a range of previous findings (Hazeltine et al., 2002; Tombu and Jolicoeur, 2004). The finding of residual dual-task costs in the present study might be due to the use of separate deadlines for dual-task and single-task conditions taken as the basis of the financial payoff matrix. This procedure might maintain strong and equal motivation for both single-task trials and dual-task trials until the end of training (Tombu and Jolicoeur, 2004). In contrast, Schumacher et al. (2001) exclusively used the performance deadline of the single-task trials presented during the mixed blocks to award financial payoff in both single-task and dual-task trials during training (see also Hazeltine et al., 2002). The Schumacher procedure might increase effects of mobilized effort in dual-task trials as compared to single-task trials. As a result of these unequal effects, one should find a greater reduction of RTs in dual-task than in single-task during training. This difference in deadline procedures between studies might explain the finding of non-significant dual-task costs in the study by Schumacher and colleagues (i.e., perfect time sharing) in contrast to the small residual dual-task costs we found at the end of training (i.e., near perfect time sharing).

In the terminology of the testing the limits approach, we provided evidence that, under very specific conditions, the developmental reserve of older adults enables optimized dual-task performance. Although further studies are needed to better understand how and when age impairs the ability to perform concurrent tasks, the results reported here, along with previous training studies (e.g., Maquestiaux et al., 2004; Allen et al., 2009; Hartley et al., 2011), suggest that the ability to dual-task can be substantially improved in older adults. Within the context of the testing the limits approach, our results suggest that age does not necessarily reduce the range of cognitive plasticity that can be achieved after substantial training. One open question of the present study, however, refers to the limits of cognitive plasticity and optimized dual-task performance in old-older adults; note that we included relatively young older adults in the present study who were largely in their sixties. From studies on other cognitive domains, it is known that with increasing age, adults are less likely to efficiently use newly acquired skills and strategies (e.g., Nyberg et al., 2003; Buschkuehl et al., 2008); thus, more elderly adults may not benefit from the present type of dual-task training to the extent of older adults. Another open question refers to the underlying practice-related mechanisms of optimized dual-task performance in older adults. These mechanisms may be associated with either processing changes within the component tasks that constitute a dual-task situation (e.g., Ruthruff et al., 2006; Maquestiaux et al., 2010) or the acquisition of improved task coordination skills in older adults. Particularly, the latter option is of interest as there exist opposing theoretical assumptions in the aging literature that are consistent (e.g., Hirst et al., 1980; Kramer et al., 1995; Bherer et al., 2005) or inconsistent (e.g., Maquestiaux et al., 2004) with such a skill acquisition.

CONCLUSION

Older adults are able to improve dual-task performance even after they have already conducted extensive prior training. Under very specific conditions (i.e., training with simplified component tasks), this age group demonstrates a similar level of optimized dual-task performance when contrasted with that performance in younger adults, i.e., near perfect time sharing. In this way, we tested the performance limits of older adults in dual-tasks and the cognitive plasticity associated in performing these situations.

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REFERENCES

Allen, P. A., Ruthruff, E., Elicker, J. D., and Lien, M. (2009). Multisession, dual-task psychological refractory period practice benefits older and younger adults equally. *Exp. Aging Res.* 35, 369–399.

Allen, P. A., Smith, A. F., Vires-Collins, H., and Sperry, S. (1998). The psychological refractory period: evidence for age differences in attentional time-sharing. *Psychol. Aging* 13, 218–229.

Anger, H., Hylla, E., Horn, H., Schwarz, E., Raatz, U., and Bargmann, R. (1968). *Wortschatztest WST 7-8. Begabungstest für 7. und 8. Klassen.* Weinheim: Verlag Julius Beltz.

Baltes, P. B., and Kliegl, R. (1992). Further testing of limits of cognitive plasticity: negative age differences in a mnemonic skill are robust. *Dev. Psychol.* 28, 121–125.

Beringer, J. (2000). *Experimental Runtime System.* Frankfurt am Main: BeriSoft Cooperation.

Bherer, L., Kramer, A. F., Peterson, M. S., Colcombe, S., Erickson, K., and Becic, E. (2005). Training effects on dual-task performance: are there age-related differences in plasticity of attentional control? *Psychol. Aging* 20, 695–709.

Bherer, L., Kramer, A. F., Peterson, M. S., Colcombe, S., Erickson, K., and Becic, E. (2006). Testing the limits of cognitive plasticity in older adults: application to attentional control. *Acta Psychol. (Amst.)* 123, 261–278.

Bherer, L., Kramer, A. F., Peterson, M. S., Colcombe, S., Erickson, K., and Becic, E. (2008). Transfer effects in task-set cost and dual-task cost after dual-task training in older and younger adults: further evidence for cognitive plasticity in attentional control in late adulthood. *Exp. Aging Res.* 34, 188–209.

Brickenkamp, R., and Zillmer, E. (1998). *The d2 Test of Attention. (1st US Edn.).* Seattle, WA: Hogrefe and Huber Publishers.

Buschkuehl, M., Jaeggi, S. M., Hutchison, S., Perrig-Chiello, P., Däpp, C., Müller, M., and Perrig, W. J. (2008). Impact of working memory training on memory performance in old-old adults. *Psychol. Aging* 23, 743–753.

Cavanaugh, J. C., and Blanchard-Fields, F. (2006). *Adult Development and Aging*, 5th Edn. Belmont, CA: Wadsworth Publishing/Thomson Learning.

Folstein, M. F., Folstein, S. E., and McHugh, P. R. (1975). "Mini mental state" – a practical method for grading the cognitive state of patients for the clinician. *J. Psychiatr. Res.* 12, 189–198.

Frith, C. D., and Done, D. (1986). Routes to action in reaction time tasks. *Psychol. Res.* 48, 169–177.

Glass, J. M., Schumacher, E. H., Lauber, E. J., Zurbriggen, E. L., Gmeindl, L., Kieras, D. E., and Meyer, D. E. (2000). Aging and the psychological refractory period: task-coordination strategies in young and old adults. *Psychol. Aging* 15, 571–595.

Göthe, K., Oberauer, K., and Kliegl, R. (2007). Age differences in dual-task performance after practice. *Psychol. Aging* 22, 596–606.

Guttentag, R. E. (1989). Age differences in dual-task performance: procedures, assumptions, and results. *Dev. Rev.* 9, 146–170.

Hartley, A. A. (2001). Age differences in dual-task interference are localized to response-generation processes. *Psychol. Aging* 16, 47–54.

Hartley, A. A., and Little, D. M. (1999). Age-related differences and similarities in dual-task interference. *J. Exp. Psychol. Gen.* 128, 417–450.

Hartley, A. A., Maquestiaux, F., and Silverman Butts, N. (2011). A demonstration of dual-task performance without interference in some older adults. *Psychol. Aging* 26, 181–187.

Hazeltine, E., Teague, D., and Ivry, R. B. (2002). Simultaneous dual-task performance reveals parallel response selection after practice. *J. Exp. Psychol. Hum. Percept. Perform.* 28, 527–545.

Hein, G., and Schubert, T. (2004). Aging and input processing in dual-task situations. *Psychol. Aging* 19, 416–432.

Hirst, W., Spelke, E. S., Reaves, C. C., Caharack, G., and Neisser, U. (1980). Dividing attention without alteration or automaticity. *J. Exp. Psychol. Gen.* 109, 98–117.

Kramer, A. F., Larish, J. F., and Strayer, D. L. (1995). Training for attentional control in dual task settings: a comparison of young and old adults. *J. Exp. Psychol. Appl.* 1, 50–76.

Kramer, A. F., and Willis, S. L. (2003). "Cognitive plasticity and aging," in *The Psychology of Learning and Motivation: Advances in Research and Theory*, Vol. 43, eds B. H. Ross and B. H. Ross (New York: Elsevier Science), 267–302.

Kray, J., and Lindenberger, U. (2000). Adult age differences in task switching. *Psychol. Aging* 15, 126–147.

Liepelt, R., Strobach, T., Frensch, P., and Schubert, T. (2011). Improved intertask coordination skills after extensive dual-task practice. *Q. J. Exp. Psychol.* 64, 1251–1272.

Lindenberger, U., and Baltes, P. B. (1995). Testing-the-limits and experimental simulation: two methods to explicate the role of learning in development. *Hum. Dev.* 38, 349–360.

Lindenberger, U., Kliegl, R., and Baltes, P. B. (1992). Professional expertise does not eliminate age differences in imagery-based memory performance during adulthood. *Psychol. Aging* 7, 585–593.

Logan, G. D., and Gordon, R. D. (2001). Executive control of visual attention in dual-task situations. *Psychol. Rev.* 108, 393–434.

Maquestiaux, F., Hartley, A. A., and Bertsch, J. (2004). Can practice overcome age-related differences in the psychological refractory period effect? *Psychol. Aging* 19, 649–667.

Maquestiaux, F., Laguë-Beauvais, M., Ruthruff, E., and Bherer, L. (2008). Bypassing the central bottleneck after single-task practice in the psychological refractory period paradigm: evidence for task automatization and greedy resource recruitment. *Mem. Cognit.* 36, 1262–1282.

Maquestiaux, F., Laguë-Beauvais, M., Ruthruff, E., Hartley, A. A., and Bherer, L. (2010). Learning to bypass the central bottleneck: declining automaticity with advancing age. *Psychol. Aging* 25, 177–192.

McDowd, J. M., and Shaw, R. J. (2000). "Attention and aging: a functional perspective," in *The Handbook of Aging and Cognition*, 2nd Edn, eds F. M. Craik, T. A. Salthouse, F. M. Craik, and T. A. Salthouse (Mahwah, NJ: Lawrence Erlbaum Associates Publishers), 221–292.

Meyer, D. E., and Kieras, D. E. (1999). "Précis to a practical unified theory of cognition and action: some lessons from EPIC computational models of human multiple-task performance," in *Attention and Performance XVII: Cognitive Regulation of Performance: Interaction of Theory and Application*, eds D. Gopher, A. Koriat, D. Gopher, and A. Koriat (Cambridge, MA: The MIT Press), 17–88.

Nyberg, L., Marklund, P., Persson, J., Cabeza, R., Forkstam, C., Petersson, K., and Ingvar, M. (2003). Common prefrontal activations during working memory, episodic memory, and semantic memory. *Neuropsychologia* 41, 371–377.

Oldfield, R. C. (1971). The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia* 9, 102–107.

Pashler, H. (1994). Dual-task interference in simple tasks: data and theory. *Psychol. Bull.* 116, 220–244.

Raz, N. (2000). "Aging of the brain and its impact on cognitive performance: integration of structural and functional findings," in *The Handbook of Aging and Cognition*, eds F. I. M. Craik and T. A. Salthouse (Mahwah, NJ: Lawrence Erlbaum Associates), 1–90.

Riby, L. M., Perfect, T. J., and Stollery, B. T. (2004). The effects of age and task domain on dual task performance: a meta-analysis. *Eur. J. Cogn. Psychol.* 16, 868–891.

Rogers, R. D., and Monsell, S. (1995). Costs of a predictable switch between simple cognitive tasks. *J. Exp. Psychol. Gen.* 124, 207–231.

Ruthruff, E., Johnston, J. C., and Van Selst, M. V. (2001). Why practice reduces dual-task interference. *J. Exp. Psychol. Hum. Percept. Perform.* 27, 3–21.

Ruthruff, E., Johnston, J. C., Van Selst, M. V., Whitsell, S., and Remington, R. (2003). Vanishing dual-task interference after practice: has the bottleneck been eliminated or is it merely latent? *J. Exp. Psychol. Hum. Percept. Perform.* 29, 280–289.

Ruthruff, E., Van Selst, M., Johnston, J. C., and Remington, R. W. (2006). How does practice reduce dual-task interference: integration, automatization, or simply stage-shortening? *Psychol. Res.* 70, 125–142.

Schubert, T. (1999). Processing differences between simple and choice reaction affect bottleneck localization in overlapping tasks. *J. Exp. Psychol. Hum. Percept. Perform.* 25, 408–425.

Schubert, T. (2008). The central attentional limitation and executive control. *Front. Bisoci.* 13, 3569–3580.

Schumacher, E. H., Seymour, T. L., Glass, J. M., Fencsik, D. E., Lauber, E. J., Kieras, D. E., and Meyer, D. E. (2001). Virtually perfect time sharing in dual-task performance: uncorking the central cognitive bottleneck. *Psychol. Sci.* 12, 101–108.

Sigman, M., and Dehaene, S. (2006). Dynamics of the central bottleneck: dual-task and task uncertainty. *PLoS Biol.* 4, e220. doi:10.1371/journal.pbio.0040220

Somberg, B. L., and Salthouse, T. A. (1982). Divided attention abilities in young and old adults. *J. Exp. Psychol. Hum. Percept. Perform.* 8, 651–663.

Strobach, T., Frensch, P. A., and Schubert, T. (2008). "The temporal stability of skilled dual-task performance," in *Cognitive Science 2007. Saarbrücken: Proceedings of the 8th Annual Conference of the Cognitive Science Society of Germany*, eds H. D. Zimmer, C. Frings, A. Mecklinger, B. Opitz, M. Pospeschill, and D. Wentura.

Strobach, T., Liepelt, R., Schubert, T., and Kiesel, A. (2012a). Task switching: effects of practice on switch and mixing costs. *Psychol. Res.* 76, 74–83.

Strobach, T., Frensch, P. A., Müller, H., and Schubert, T. (2012b). Age- and practice-related influences on dual-task costs and compensation mechanisms under optimal conditions for dual-task performance. *Aging Neuropsychol. Cogn.* 19, 222–247.

Strobach, T., Frensch, P. A., Soutschek, A., and Schubert, T. (in press). Investigation on the improvement and transfer of dual-task coordination skills. *Psychol. Res.*

Tombu, M., and Jolicoeur, P. (2004). Virtually no evidence for virtually perfect time-sharing. *J. Exp. Psychol. Hum. Percept. Perform.* 30, 795–810.

Van Selst, M., and Jolicoeur, P. (1997). Decision and response in dual-task interference. *Cogn. Psychol.* 33, 266–307.

Van Selst, M., Ruthruff, E., and Johnston, J. C. (1999). Can practice eliminate the psychological refractory period effect? *J. Exp. Psychol. Hum. Percept. Perform.* 25, 1268–1283.

Verhaeghen, P. (2011). Aging and executive control: reports of a demise greatly exaggerated. *Curr. Dir. Psychol. Sci.* 20, 174–180.

Verhaeghen, P., Steitz, D. W., Sliwinski, M. J., and Cerella, J. (2003). Aging and dual-task performance: a meta-analysis. *Psychol. Aging* 18, 443–460.

Weiß, R. H. (2006). *CFT 20-R: Grundintelligenztest Skala 2 – Revision.* Göttingen: Hogrefe.

West, R. L. (1996). An application of prefrontal cortex function theory to cognitive aging. *Psychol. Bull.* 120, 272–292.

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Online games training aging brains: limited transfer to cognitive control functions

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The prevalence of age-related cognitive decline will increase due to graying of the global population. The goal of the present study was to test whether playing online cognitive training games can improve cognitive control (CC) in healthy older adults. Fifty-four older adults (age 60–77) played five different cognitive training games online for 30 min a day over a period of seven weeks (game group). Another group of 20 older adults (age 61–73) instead answered quiz questions about documentaries online (documentary group). Transfer was assessed by means of a cognitive test battery administered before and after the intervention. The test battery included measures of working memory updating, set shifting, response inhibition, attention, and inductive reasoning. Compared with the documentary group, the game group showed larger improvement of inhibition (Stop-Signal task) and inductive reasoning (Raven-SPM), whereas the documentary group showed more improvement in selective attention (UFoV-3). These effects qualify as transfer effects, because response inhibition, inductive reasoning and selective attention were not targeted by the interventions. However, because seven other indicators of CC did not show benefits of game training and some of those that did suffered from potential baseline differences, the study as a whole provides only modest support for the potential of videogame training to improve CC in healthy older adults.

Keywords: videogames, cognitive control, far transfer, cognitive enhancement, aging

INTRODUCTION

The proportion of people over age 65 is steadily increasing worldwide (United-Nations, 2010). Given that cognitive functions decline with age (Meijer et al., 2009), age-related cognitive decline is becoming increasingly prevalent. Although there is a variety of effects of healthy old age on cognition, those on cognitive control (CC) functions have the most ubiquitous consequences (Burgess et al., 1998), as they are relevant for the selection and integration of information (Wild-Wall et al., 2011) and for dealing with novel situations that call for a deviation from automatized behavioral routines (Kramer et al., 1994; Wild-Wall et al., 2011). Impaired CC can therefore have serious consequences for the independence and quality of life of older adults. Fortunately, cognitive plasticity is preserved even at a very old age (Singer et al., 2003; Buschkuehl et al., 2008), so with the right interventions it seems feasible to reduce the dependence on caregivers and improve the quality of life in old adulthood.

Videogames have been recognized as a powerful tool for cognitive enhancement (Green and Bavelier, 2008). Indeed, positive effects of playing videogames on CC in old adults have been demonstrated (Basak et al., 2008; Peretz et al., 2011; Nouchi et al., 2012). Recently, however, a large-scale online study of videogame training among adults of all ages failed to show transfer of proficiency from trained tasks to untrained probe tasks (Owen et al., 2010). Although it successfully demonstrated that cognitive training is not a panacea, there is a risk that Owen et al.'s conclusions prematurely discredit videogame training, particularly in view of previous positive findings and the great potential it holds for buffering cognitive aging (Basak et al., 2008). Therefore, the current study addressed the need to clarify which CC functions can be enhanced by game training in healthy older adults, and whether there is transfer between the trained and untrained functions.

The study strictly followed methodological recommendations from the literature. First, an active control group was included in the experimental design to match the amount of computer use, adherence to a training schedule, and expectancy effects (Klingberg, 2010) to an extent that cannot be achieved by means of a waiting list control group. These participants watched documentaries and answered quiz questions online (Dustman et al., 1992). Second, we tested older adults on a series of CC tests before and after a substantial intervention (Klingberg, 2010), amounting to up to 49 videogame or documentary sessions. Transfer to cognitive domains subjected to training as well as transfer to untrained cognitive domains was assessed. The choice of transfer tasks was based on Miyake et al.'s (2000) taxonomy of CC functions as validated by latent variable analysis and, in contrast to Owen et al. (2010), the pretest and post-test measurements were taken under standardized laboratory conditions. Finally, the design of the online videogame training program was optimized according to recommendations of Green and Bavelier (2008). That is, the stimulus variability was high, difficulty levels of the games were continuously adapted to performance, and feedback and motivational messages were provided frequently. The design is also in accordance with empirically based recommendations for optimal learning as defined outside the context of game research. For example, in order to attain a higher level of performance large amounts of deliberate practice are required (Ericsson et al., 1993). The 49 times 30 min assigned in the current study will not raise the proficiency to expert levels, but it is a relatively long series in comparison with other game studies [e.g., 20 times 15 min in Nouchi et al. (2012); 24 times 10 min in Owen et al. (2010); 15 times 90 min in Basak et al. (2008)]. Typically deliberate practice is considered to be an effortful activity that can be sustained only for a limited time. However, not only are sessions limited to 30 min per day, the game context serves to reduce this burden and maintain motivation. Furthermore, as Schmidt and Bjork (1992) have reviewed, retention of learning benefits from the mixing of the training tasks, variability of the context, and relatively high task difficulty that were all present in the current study.

COGNITIVE CONTROL

CC functions (Botvinick et al., 2001)—also referred to as executive functions (Miyake et al., 2000)—configure other cognitive functions for the performance of the task at hand. CC can be employed for biasing perceptual channels, actions, and memory representations on the basis of a task set. Because CC is involved in a wide variety of specific tasks and contexts, improving CC potentially buffers effects of cognitive aging. Miyake et al.'s (2000) taxonomy of CC functions was adopted in the current study, because it is widely accepted and empirically validated, and because it has proved to be valuable in analyzing age effects (Salthouse et al., 2003; Fisk and Sharp, 2004; Huizinga et al., 2006). The taxonomy describes CC as emerging from three distinct cognitive processes: switching between attentional sets or task sets (shifting), monitoring and updating information in working memory (updating), and inhibiting habitual, automatic, or prepotent responses (inhibition). Cognitive tests loading on these factors were included in the test battery used in the current study. In addition, selective and divided attention was assessed, to accommodate taxonomies of CC based on attentional processes (Posner and DiGirolamo, 1998).

CC takes a long time to fully develop in the course of childhood and eventually declines in the course of late adulthood (Zelazo et al., 2004; Kray et al., 2008). Decline of CC in old adults has been observed in both cross-sectional and longitudinal studies. Compared to younger adults, maintenance, and coordination of two alternating task sets in working memory (Mayr et al., 1996; Salthouse et al., 1998; Kray and Lindenberger, 2000; Kray et al., 2008), inhibitory control (Coubard et al., 2011) and divided and selective visual attention (Edwards et al., 2006) are impaired in healthy older adults. Longitudinal data from the Maastricht Aging Study (Meijer et al., 2009), the Berlin Aging Study (Lindenberger and Ghisletta, 2009), and the Advanced Cognitive Training for Independent and Vital Elderly study (Tucker-Drob, 2011) support the notion that the full range of CC functions declines with age. A recent analysis of longitudinal data from the Victoria Longitudinal Study (Macdonald et al., 2011) revealed that the rate of cognitive decline does increase with age, but remains slow and steady until the end of life. In the context of a graying global population, these developmental trends are alarming, because impaired CC is associated with impaired functioning in daily life (Burgess et al., 1998).

PLASTICITY OF COGNITIVE CONTROL FUNCTIONS

According to the cognitive-enrichment hypothesis (Hertzog et al., 2009), the trajectory of cognitive development across the life span is not fixed. Although the trajectory of cognitive development at old age is largely determined by a lifetime of experiences and environmental influences, there is potential for discontinuity in the trajectory given a change in cognition-enriching behaviors. The cognitive-enrichment hypothesis is corroborated by ample evidence for plasticity—i.e., the potential for improvement of ability as a consequence of training (Denney, 1984)—of CC in the elderly population. Improvements of updating (Baron and Mattila, 1989; Buschkuehl et al., 2008; Dahlin et al., 2008), as well as shifting (Sammer et al., 2006; Bherer et al., 2008) and inhibition (Davidson et al., 2003; Karbach and Kray, 2009) in the population of older adults have been reported. In addition, selective attention (Ball et al., 2007) and inductive reasoning (Schmiedek et al., 2010) can be improved in older adults.

The virtue of a cognitive-training technique depends on the generalization—or transfer—of training to untrained tasks (Klingberg, 2010). Different degrees of transfer can be distinguished. Improvement within the same cognitive domain as subjected to training, assessed using different stimuli, and requiring a different response than the training task, is the minimal degree of transfer that can occur. This type of transfer is referred to as near transfer. Improvement of abilities in other cognitive domains than the cognitive domain subjected to training is referred to as far transfer.

Videogames are considered to provide an ideal context for cognitive enrichment (Achtman et al., 2008; Green and Bavelier, 2008). The characteristics of videogames presumed to facilitate transfer are their motivating nature, frequent presentation of feedback, precise reinforcement schedules, and stimulus variability (Gee, 2007). As a result of their entertainment value, videogames maintain the motivation to engage in practice for much longer than monotonous laboratory tasks or traditional training programs. Frequent feedback supports motivation and is also important for conditioning the desired level of performance. When the difficulty level of the game is continuously adapted to the performance, players will constantly be challenged at the limits of their ability. It is in particular the phase of skill-acquisition that calls for CC, whereas continued performance at a mastered level is associated with automatization and release of CC resources (e.g., Shiffrin and Schneider, 1977; Logan, 1988). Furthermore, small increments of difficulty level maximize the proportion of successful experiences with the game. Stimulus variability also plays an important role in training CC, because it helps to generalize learnt cognitive skills to multiple stimulus contexts.

Transfer of videogame interventions to CC has, however, not been demonstrated consistently. Owen et al. (2010), for instance, demonstrated that playing computerized cognitive training games like Nintendo's® Dr. Kawashima's Brain Training™ was not more beneficial for CC functions than answering general knowledge questions online. Because the sample of participants in Owen et al.'s study was very heterogeneous and included both young and old adults, it is well possible that improvements of cognitive test performance were attenuated in young adults due to ceiling performance at pretest. This could have obscured possible transfer of training in the subsample of older adults. The notion that sample heterogeneity can confound the observed effect of videogame training substantially is corroborated by Feng et al. (2007). They found no effect of playing action videogames on spatial attention in a sample of young adults. However, separate analyses of the effect in males and females revealed that females did actually benefit from playing videogames. In addition, Owen et al.'s participant sample was very heterogeneous with respect to training adherence, so participants who completed only two training sessions could have had a negative impact on aggregated training outcomes. Another aspect of Owen et al.'s study that makes the observed absence of transfer difficult to interpret is that transfer was assessed using a test battery comprising only four cognitive tests, three of which were measures of working memory capacity.

Ackerman et al. (2010) demonstrated that sample heterogeneity cannot account for Owen et al.'s (2010) findings. They found that playing cognitive training games (Nintendo® Wii™ Big Brain Academy™) does not benefit cognitive abilities to a greater extent than reading assignments do, in a homogeneous sample of healthy older adults on a relatively fixed and extensive training schedule. Moreover, a broader assessment of cognitive abilities of interest was made than in Owen et al.'s study. Still, Ackerman et al. focused predominantly on reasoning ability and perceptual processing speed, while a large share of the videogames under study taxed working memory updating and the large variety of videogames probably stimulated participants' attention and task set shifting. Inclusion of transfer tasks gauging working memory updating and set shifting in Ackerman et al.'s study could have led to different conclusions regarding transfer of playing cognitive training games.

Conversely, there is also some evidence against Owen et al.'s (2010) and Ackerman et al.'s (2010) pessimistic conclusions regarding the beneficial effects of playing videogames on CC functions. Namely, Peretz et al. (2011) found a larger improvement of visuospatial working memory, visuospatial learning, and focused attention after playing Cognifit Personal Coach® cognitive training games than after playing conventional videogames that were matched for intensity, in a sample of older adults. Even though there is some theoretical overlap in the cognitive functions assessed by Peretz et al. and Owen et al. and Ackerman et al., the specific cognitive tests used to assess transfer in these studies was different. It is conceivable that some cognitive tests are more sensitive to transfer effects than others, which might explain the discrepant results of these studies.

Furthermore, playing videogames not specifically designed for cognitive training can also improve CC functions in older adults. Basak et al. (2008) demonstrated that playing a particular complex 3-D real-time strategy game (Rise of Nations) was associated with greater improvements of shifting, updating, and inductive reasoning than observed in the control condition. It must be noted that the control group in this study was a no-contact control group, so it is not certain to what extent the observed improvements in the videogame group are attributable to placebo-effects. Nevertheless, the improvements of CC in this study were larger than practice effects due to repeated exposure to the same cognitive test.

It has been argued that failures to demonstrate far transfer of playing cognitive training games in the population of older adults may be due to a general age-related decrease of the extent to which learning transfers to untrained abilities (Ackerman et al., 2010). This assertion is supported by Ball et al.'s (2002) finding that cognitive strategy training programs for improving memory, processing speed and reasoning, respectively, were associated with improvements within the trained cognitive domain but not with far transfer to untrained cognitive abilities of older adults. In contrast, however, far transfer of practicing basic cognitive tests has been reported repeatedly in the cognitive aging literature (Mahncke et al., 2006; Uchida and Kawashima, 2008; Karbach and Kray, 2009; Smith et al., 2009). Brain training games like Nintendo's® Dr. Kawashima's Brain Training™ share many task components of basic cognitive laboratory tasks and videogames have several additional characteristics facilitating transfer (Green and Bavelier, 2008). Therefore, it is reasonable to expect that transfer of computerized cognitive training games in the population of older adults is replicable.

CURRENT STUDY

It is difficult to reconcile inconsistent findings pertaining to the effect of playing cognitive training games on cognition (Ackerman et al., 2010; Owen et al., 2010; Peretz et al., 2011), because the methodological differences between these studies are substantial. More research is required to elucidate what aspects of brain training games facilitate transfer to untrained cognitive abilities. Hence, the aim of the present study was to test whether playing brain training games does transfer to different measures of CC in healthy older adults. An online brain training game intervention (Owen et al., 2010; Peretz et al., 2011) was compared to an intervention requiring participants to watch documentaries and answer quiz questions online (Dustman et al., 1992). Transfer was assessed by comparing performance on a battery of cognitive tests before and after the intervention. Taking into account that some cognitive tests may be more sensitive to transfer effects than others, several measures of updating, shifting, and inhibition were included in the test battery. To avoid transfer effects beyond the currently used taxonomy of CC from being overlooked, measures of selective attention and inductive reasoning were also included in the test battery. While improvement on CC measures is to be expected in both groups, the crucial test is whether the improvement in the videogame condition exceeds that of the documentary condition.

Two of the games—Firemen and Falling Bricks—were specifically designed to tax updating. In these task, the speed by which participants had to update their working memory content was pushed to the limits. Two of the games were designed to tax shifting; Giving Change and Firemen. In both games, performance required switching between addition and subtraction. As for Anagrams and Telling Time, these were chosen because it is plausible that these tasks put a high demand on CC and working memory maintenance, and because they are part of the

Nintendo set. Based on the task demands of these games and evidence for near transfer of cognitive training games (Ball et al., 2002; Peretz et al., 2011), near transfer of training to updating and shifting was expected. Measures of inhibition, reasoning, and selective attention were included in the cognitive test battery, but these cognitive functions were not primarily targeted by the training program. Thus, possible improvements thereof could be considered a demonstration of far transfer. Far transfer can be expected based on ample evidence for far transfer of cognitive training in the population of older adults (Mahncke et al., 2006; Uchida and Kawashima, 2008; Karbach and Kray, 2009; Smith et al., 2009). However, there is also evidence to suggest that cognitive training games are perhaps too different from transfer task for transfer of learning to occur in older adults (Ackerman et al., 2010).

MATERIALS AND METHODS

PARTICIPANTS

Ninety-two participants were recruited through advertisements in a local newspaper and on the internet. Ten participants prematurely withdrew from the study, six in the documentary group (24%) and four in the videogame group (7%, $\chi^2_{(1)} = 5.2$, $p < 0.05$). Another eight participants could not complete the intervention due to technical issues, time constraints, or medical problems. Two additional participants with a Mini Mental State Examination (MMSE; Folstein et al., 1975) score lower than 27 out of 30 points were excluded from the analyses. Data of the remaining 72 participants were analyzed. All these participants were community dwelling citizens, free of neurological deficits or traumatic brain injury, and cognitively healthy according to prevalent MMSE norms. Prior to the study, participants in the videogame group did not differ from participants in the documentary group with respect to age, years of education, Raven IQ (Raven, 1938), MMSE score and previous computer game experience (**Table 1**). Full participation was rewarded with €100. All participants gave their informed consent prior to participation. The study was approved by the Ethical Committee of the Institute of Psychology, Leiden University.

MATERIALS

The online intervention programs were developed using Adobe Authorware 7 (©Adobe Systems Incorporated, 2011). Cognitive tests were programmed in E-prime 2.0 (©Psychology Software Tools, Inc., 2010). A PC with a 15″ CRT monitor with a refresh rate of 85 Hz was used for the administration of cognitive tests. Auditory stimuli were presented by means of headphones.

PROCEDURE

The experimental design was a randomized controlled trial. Consistent with the recommendations of (Boot et al., 2011), participants were told that the study compared two brain training interventions, without reference to either condition as the control or test condition. Participants in both groups were motivated to do well on the intervention, by means of the same set of motivational messages incorporated in the intervention programs. Participants in the videogame group played five randomly alternating videogames. The videogames were custom built, inspired by commercially available cognitive training games. Feedback on performance was presented after every response. The difficulty level of each game was raised or lowered depending on the performance in the preceding round of the respective game. Participants in the documentary group watched documentaries with a duration of approximately 30 min. A different documentary was presented every session. After watching a documentary, participants had to answer three to five multiple-choice quiz questions about the documentary. The same feedback stimuli as used in the videogames were presented after every response. Participants were instructed to complete one 30-min intervention session per day, every day of the week, for seven weeks, resulting in a total of up to 24.5 h of training. Participants who were unable to complete a session on one day were instructed to complete an extra session on another day. The intervention was available online, hosted on a faculty server. This enabled participants to complete the intervention program at home and it allowed the experimenters to track intervention compliance and performance.

All participants completed a cognitive test battery comprising nine cognitive tests before and after the intervention. In addition, participants were subjected to the MMSE and completed a general health questionnaire at pretest. The pre- and post-test assessments were conducted in the cognitive-psychology laboratory of Leiden University. Three different test sequences were devised and these were counterbalanced across participants. Each participant completed the test battery in the same order at pre- and post-test. The test battery took approximately two hours to complete. Participants were allowed to take a 10-min break after the first hour of testing.

Table 1 | Distribution of males and females across conditions and mean (SD) age, years of education, MMSE score, and Raven SPM IQ in each condition.

	Experimental group	Documentary group		
Gender	$n_{male} = 25$	$n_{male} = 15$	$\chi^2_{(1)} = 5.7$	$p < 0.05$
	$n_{female} = 28$	$n_{female} = 4$		
Age	67.8 (3.8)	67.2 (3.4)	$t_{(70)} = 0.7$	$p > 0.05$
Years of education	13.2 (4.4)	11.8 (3.4)	$t_{(70)} = 1.2$	$p > 0.05$
MMSE	28.8 (1.2)	28.9 (0.9)	$t_{(70)} = -0.2$	$p > 0.05$
Raven SPM IQ	115.7 (12.3)	120.1 (9.8)	$t_{(70)} = -1.4$	$p > 0.05$
Played videogames	25%	24%	$\chi^2_{(1)} < 1$	$p > 0.05$

VIDEOGAMES

The videogames were presumed to tax CC, as they required players to select and integrate information, manipulate working memory representations, and switch between task sets.

Anagrams

In the Anagrams game (**Figure 1A**) a different string of letters was presented every game round. Players were instructed to spell a new word using all of the presented letters. At the lowest difficulty level anagrams were three letters long. The most difficult anagrams were nine letters long. As players advanced, the length of the presented letter strings increased.

Falling bricks

In the Falling Bricks game (**Figure 1B**) an animation of bricks falling down behind an occluding rectangle was presented. The occluding rectangle was subdivided into several columns. After the animation, players had to indicate how high the stack of bricks in one cued column was. As players advanced, the total number of falling bricks and the number of columns constituting the occluding rectangle, increased. The number of columns to monitor ranged from 1 to 10. The number of falling bricks ranged from 1 to 11.

Telling time

In the Telling Time game (**Figure 1C**) an analog clock was presented. Players were instructed to indicate what time it would be after a variable number of hours and minutes, given the current time depicted on the clock. As players advanced, the complexity of the time addition increased. At the lowest difficulty level the time difference was 3 h at most. At the highest level, the time difference was 24 h at most.

Giving change

In the Giving Change game (**Figure 1D**) players were presented with a price to be paid and a payment that has been made. The player's task was to return change by clicking the optimal combination of bills and coins. As players advanced, the presented prices and payments increased. At the lowest difficulty level the presentation time of the price and the change the player had already returned, were presented for an infinite amount of time. In addition, the highest price was €5 and players were allowed to return five coins and bills more than minimally necessary to make the correct change. At the highest difficulty level the prices were presented for only 3 s, no online feedback was provided regarding the amount already returned, the maximum payment was €500 and no more coins or bills than necessary were allowed to be returned.

Firemen

In the Firemen game (**Figure 1E**) an animation of several groups of stick figures moving into or out of a house was presented. Groups of one to five stick figures were presented at a time. Players were required to keep track of the number of stick figures inside the house. After the animation, players were prompted to type in the remaining number of stick figures residing in the house. As players advanced, stick figures walked into and out of the house with greater frequency and in larger numbers.

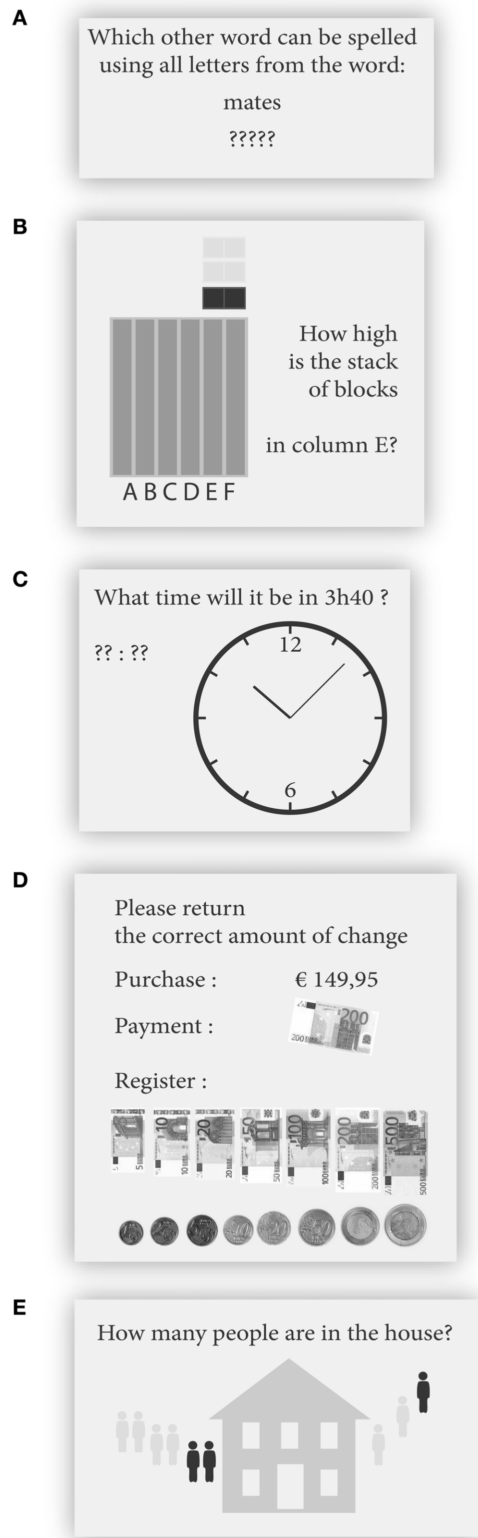

FIGURE 1 | Impression of the games constituting the game intervention. (A) Anagrams, **(B)** Falling Bricks, **(C)** Telling Time, **(D)** Giving Change, **(E)** Firemen. All text was presented in Dutch.

COGNITIVE TEST BATTERY

Mini mental state examination

The MMSE is the most widely used assessment of global cognitive function (Folstein et al., 1975). It is often used to screen for dementia or monitor its progression. A Dutch version of the test was used.

Stroop color-word test

In a computerized version of the Stroop Color-Word Test (Stroop, 1935) participants were instructed to ignore a visually presented Dutch color name ("rood," "blauw," or "groen") corresponding to either red, blue, or green and identify the font color of the stimulus (red, blue, or green) as quickly as possible by choosing a keyboard key ("C," "V," or "B"), each corresponding to a stimulus color. The mapping of stimulus colors to buttons was balanced across participants. All possible combinations of stimulus color and color name were presented 20 times in random order. The test consisted of four blocks of 45 trials, separated by short breaks. A trial started with the 1500 ms presentation of a central fixation cross. Subsequently, a stimulus was presented centrally for a maximum duration of 3000 ms or until a response was detected. The response-stimulus interval (RSI) was randomized (600–800 ms). Only reaction times (RT) associated with correct responses were analyzed. The mean RT difference between the incongruent and congruent conditions was used as a dependent variable, which is assumed to measure inhibition (Miyake et al., 2000).

Stop-signal test

In the Stop-Signal Test (Logan et al., 1984), each trial started with a fixation cross presented for 250 ms, followed by an "O" or "X" in the center of the screen lasting for 2000 ms, or until a response was detected. Participants were instructed to indicate which of the two stimuli was presented by pressing one of two keyboard keys ("C" or "N"). Stimulus-response mappings were balanced across participants. In addition, participants were instructed to try to withhold their response if they heard a computer-emitted tone on 33% randomly selected trials, but not to slow down in anticipation of stop signals. Participants practiced nine trials before the actual experiment started. The experiment consisted of 3 blocks of 36 trials. The stimulus onset asynchrony (SOA) of the visual stimulus and the auditory stop signal started at 30 ms and varied depending on stop success following a staircase algorithm aiming at 50% accuracy, with step sizes of 30 ms and a maximum SOA of 700 ms. Stop-signal reaction time (SSRT), defined as the difference between median RT in GO-trials and mean SOA (Band et al., 2003) was used as dependent variable. To obtain a reliable measure of SSRT, the analysis was limited to participants with 10–90 percent correct inhibition and at least 60 percent accuracy on nonsignal trials. The Stop-Signal Test is considered a measure of inhibition (Logan et al., 1984).

Counting span

The Counting Span task (Conway et al., 2003) required participants to count the number of blue circles within serially presented stimulus arrays. After a series of stimulus arrays was presented, participants were prompted to recall the total number of blue circles in each stimulus array, in the correct order. The stimulus arrays also contained distracters with either the same shape or the same color as the target stimulus. Participants first practiced four trials, each consisting of a series of two stimulus arrays. Trials in the subsequent experimental block could consist of two to five stimulus arrays. All trial types were replicated three times. The order of trial types was pseudo-randomized and stimulus presentation was self-paced. Participants were instructed to count the targets out loud, repeat the total number of targets out loud and press the spacebar on the keyboard to advance to the next stimulus array. After the last stimulus array, participants were prompted to type in the recalled number of targets in each stimulus array presented in the current trial. The total number of correctly recalled counts in the condition with highest memory load was used as dependent variable. The counting span task can be considered as a measure of updating (Schmiedek et al., 2009).

Mental counters

The Mental Counters task (Larson and Saccuzzo, 1989) required participants to keep track of multiple variable numbers. Each number to be updated was represented by a horizontal bar on the screen. The number started at a value of five and had to be increased or decreased whenever an "X" was presented above or below the bar, respectively, and should not be changed if an "?" was presented. The inter-stimulus interval was 1700 ms. After five or six updates, participants were prompted to enter the final value of each number at their own pace. The test consisted of 2 blocks of 10 trials. Participants had to keep track of two numerical representations in the first block and three numerical representations in the second block. The number of updates required was randomized across trials. The mean number of correct responses in the condition with three numbers was used as dependent variable. The mental counters task provides a measure of updating (Huizinga et al., 2006).

Useful field of view test

A divided attention and a selective attention subtest of the Useful Field of View Test (Edwards et al., 2005) were administered. In both subtests, participants were instructed to identify the shape of a briefly presented central car or truck stimulus and the location of simultaneously presented peripheral car stimulus. The peripheral target could appear at one of eight radial locations. In the selective attention subtest, the empty parts of the stimulus display were filled up with distracters (triangles). A fixation box was presented at the beginning of a trial. Next, both stimuli were presented simultaneously. The screen was filled with a white-noise visual mask immediately after stimulus presentation. Then, two response screens appeared consecutively, prompting for the identity of the central stimulus and the location of the peripheral stimulus by mouse clicks. The duration of stimulus presentation was determined by a staircase algorithm aiming at 75% accuracy. The duration of stimulus presentation associated with 75% accurate performance on the divided (UFoV2) and selective attention (UFoV3) subtest was used as dependent variable.

Raven standard progressive matrices

The Raven's Standard Progressive Matrices (Raven-SPM; Raven, 1938) consists of textural patterns and 3 × 3 matrices of figures from which one part is missing. Participant were required to indicate which of six or eight alternatives correctly completed the presented pattern. We used a shortened, computerized version of the Raven SPM (Keizer et al., 2010), consisting of either the 30 even or 30 odd items, with a time limit of 10 min. One subset was administered at pretest and the other at post-test in balanced order. Raven IQ scores corrected for age (Peck, 1970) were used as dependent variable. The Raven-SPM test provides a measure of inductive reasoning ability (Schmiedek et al., 2009).

Global-local switching test

In the Global-Local Switching Test (Huizinga et al., 2006), participants were required to respond to either the local or the global shape of a large square or rectangle consisting of small squares or rectangles. The size of these response alternatives displayed at the bottom of the screen indicated whether the participant was required to match the response to the local or global shape of the stimulus. The relevant size (global vs. local) was constant in two pure blocks, and varied randomly in two mixed blocks of 30 trials. The order of blocks and relevant stimulus dimensions was counterbalanced across participants. A practice block of eight trials preceded the actual experiment. At the beginning of each trial a central fixation cross was presented for 200–400 ms (randomized). The response alternatives were presented next. The stimulus was added to the display with a 500 ms delay. A trial ended after 4000 ms or when a response was detected. RSI was 500 ms. Switch cost was used as dependent variable (Karbach and Kray, 2009). Switch cost was defined as average RT difference between trials with switched versus repeated size instructions, within the mixed block. The Global-Local Switching Test provides a measure of shifting (Huizinga et al., 2006).

Smiling faces switching test

The Smiling Faces Switching Test (Huizinga et al., 2006) required participants to respond to either the emotional expression or gender of faces. The stimuli were simple line drawings of a male or female face with a happy or sad facial expression. Stimuli could appear in one of the quadrants of a 2×2 grid. The relevant stimulus dimension was determined by the row in which a stimulus was presented. The mapping of relevant stimulus dimensions on rows was balanced across participants. Trials were blocked in exactly the same fashion as in the Global Local Switching Test. Participants were instructed to respond by pressing the "Z" or "M" key. Each key was associated with one facial expression and one gender. Stimulus-response mappings were balanced across participants. At the beginning of each trial a central fixation cross was presented for 200–400 ms (randomized). Subsequently, the stimulus was presented for 4000 ms or until a response was detected. The RSI was randomized (200–400 ms). Switch cost was used as dependent variable (Span et al., 2004).

Test of attentional performance

The Test of Attentional Performance (Majer et al., 2004) requires participants to perform a visual discrimination task and an auditory 1-back task in parallel. In the visual task a 4 by 4 grid consisting of dots and crosses was presented on each trial. Subjects were instructed to press the "C" key on the keyboard if a square of crosses was formed on any four adjacent points on the grid. In the auditory 1-back task either a high-pitch (990 Hz) or low-pitch (660 Hz) tone was presented every trial. Subjects were instructed to press the "V" key on the keyboard if the currently presented tone had the same pitch as the tone presented on the previous trial. Participants were instructed to pay attention to both tasks at the same time and react as fast as they could while maintaining a high level of accuracy. Participants first completed three practice blocks consisting of six trials. In the first two practice blocks, the individual tasks were practiced in isolation. In the third practice block participants practiced the dual task. After the practice blocks, participants completed three experimental blocks consisting of 60 trials. The inter-stimulus interval was 2900 ms when no response was detected. The RSI was 800 ms. Although participants were instructed to perform both tasks in parallel, a target was never presented in both modalities simultaneously. The accuracy of target detection was used as dependent variable. The Test of Attentional Performance is considered to be a measure of divided attention (Majer et al., 2004).

RESULTS

VIDEOGAME PERFORMANCE

The time spent on the intervention did not differ statistically between the videogame ($M = 21.1$ h, $SD = 3.3$) and the documentary group ($M = 22.9$ h, $SD = 3.9$; $t_{(71)} = 2.0$, $p > 0.05$). Participants reached increasingly higher levels in all the games. The use of statistical tests in analyzing game level progress would be misleading, however. Games are not suited to yield accurate capability scores for each session, for example because starting levels were deliberately easy to perform and multiple parameters changed with each successive level. Suffice it to note, therefore, that on average the participants eventually managed to solve anagrams of 7 letters ($SD = 0.4$), and monitored 6.5 ($SD = 1.9$) columns during 6.9 ($SD = 2.0$) updates in the Falling Bricks game. In the Fireman game, 9.4 ($SD = 0.9$) updates were made, with speeds of 753 ms ($SD = 188$ ms) per update. All participants were eventually able to complete the Telling Time and the Giving Change game at the highest difficulty level.

The subjective experience of the videogame and documentary intervention was not systematically assessed, but a surprisingly large proportion of participants left remarks about their experience of the intervention in the general exit questionnaire. Although these data are confounded by response bias, they still give some, albeit tentative, insight into the success of the intervention. Sixty-six percent of participants in the videogame group reported about how much they enjoyed the intervention, compared to 90% in the documentary group. Fifty-one percent of all participants and 77% of responding participants in the videogame group stated to have enjoyed the intervention. Thus, 23% of all participants in this condition indicated that they had not enjoyed the videogames without being inquired about it. In the documentary group, 79% of all participants and 88% of responding participants indicated that they enjoyed the intervention. Only 12% of all participants in this condition indicated that they had not enjoyed the documentaries without being inquired about it.

TRANSFER

For the Stroop test, UFoV-3, Smiling Faces Switching Test and Global Local Switching Test, trials with RTs outside a 2 SD range were excluded for each participant. For each dependent variable, participants with individual mean scores outside a 3.5 SD range per group were excluded. Repeated-measures ANOVA with Intervention (videogame vs. documentary) as between-subject factor and Time (pre-test vs. post-test) as within-subject factor were conducted to analyze transfer of training to each dependent variable separately. The interaction effect of Intervention and Time was significant on SSRT, UFoV-3, and Raven IQ. These effects were small to medium sized ($\eta_p^2 < 0.10$). The results of all univariate analyses are summarized in **Table 2**, and mean scores are summarized in **Table 3**.

As expected, the improvement of Stop-Signal task and Raven-SPM performance was larger in the videogame group than in the documentary group (**Figure 2**). The mean SSRT decreased from 326 ms at pretest to 250 ms at post-test in the videogame group. In the documentary group the mean SSRT decreased from 246 to 240 ms. The mean Raven IQ scores were above Peck's (1970) average norm scores in both groups at both assessments. In the videogame group, mean Raven IQ increased from 116 at pre-test to 119 at post-test, while mean Raven IQ decreased from 120 to 117 in the documentary group. However, contrary to expectations, the improvement of UFoV-3 performance was larger in the documentary group than in the videogame group. The videogame group improved from 276 ms at pretest to 261 ms at post-test, while the documentary group improved from 273 ms to 208 ms. The change of performance from pre-test to post-test on all dependent variables in the videogame group and the documentary group is illustrated in **Figure 2**.

The significant interaction effects were further analyzed by means of simple effect analyses of the difference between pre-test and post-test performance within each intervention group (**Figure 2** and **Table 4**). The improvement of SSRT was significant in the videogame group, while there was no significant change of SSRT over time in the documentary group. The improvement of SSRT in the videogame group can be considered a large effect (Cohen, 1992). The increase of Raven IQ in the videogame group was marginally significant, as was the decrease in Raven IQ in the documentary group. The improvement of UFoV-3 was only significant in the documentary group and was also large.

Table 2 | Results obtained from univariate ANOVA of the interaction effect of Intervention and Time on every dependent variable.

Test	Statistic	Significance	Effect size (η_p^2)
Raven SPM	$F_{(1, 69)} = 5.0$	$p < 0.05$*	0.068
Stroop	$F_{(1, 67)} < 1$	$p > 0.1$	0.001
Stop-signal	$F_{(1, 54)} = 5.2$	$p < 0.05$*	0.087
Mental counters	$F_{(1, 69)} < 1$	$p > 0.1$	0.011
Counting span	$F_{(1, 68)} < 1$	$p > 0.1$	<0.001
Smiling faces	$F_{(1, 69)} = 1.7$	$p > 0.1$	0.024
Global local	$F_{(1, 66)} < 1$	$p > 0.1$	<0.001
TAP	$F_{(1, 68)} < 1$	$p > 0.1$	<0.001
UFoV-2	$F_{(1, 69)} < 1$	$p > 0.1$	<0.001
UFoV-3	$F_{(1, 68)} = 4.3$	$p < 0.05$*	0.059

*, *p < 0.05.*

Post-hoc ANALYSES

There were two issues that required further elaboration to fully appreciate the value of the transfer effects. First, the analysis of the participants' background characteristics revealed that the videogame and documentary group were significantly unbalanced in terms of gender composition. Considering Feng et al.'s (2007) finding that gains in spatial attention due to playing action videogames were larger for women than for men, the transfer effects observed in the present study may be confounded by the dissimilar gender composition of the videogame group and the documentary group. Three-way repeated-measures ANOVA including Gender (male vs. female) and Intervention (videogame vs. documentary) as between-subject factors, and Time (pre-test vs. post-test) as within-subject factor were conducted to falsify this alternative explanation of the observed transfer effects. The Gender X Intervention X Time interaction effects on SSRT, UFoV-3, and Raven IQ were all not significant (all *F*s < 2,

Table 3 | Mean (SE) scores for the cognitive indices used, divided by group and test time.

Index	Videogame Group Mean (SE)		Documentary Group Mean (SE)	
	Pre-test	Post-test	Pre-test	Post-test
IQ Raven SPM	116.4 (1.5)	119.4 (1.5)	120.1 (2.5)	116.8 (2.5)
Stroop	156.6 (18.7)	155.7 (15.5)	113.8 (31.5)	105.8 (26.0)
Stop-signal	326.2 (18.8)	249.8 (12.3)	245.6 (28.5)	239.9 (18.6)
Mental counters	1.67 (0.10)	2.05 (0.10)	1.82 (0.16)	2.05 (0.16)
Counting span	12.6 (0.3)	13.3 (0.3)	12.7 (0.5)	13.1 (0.5)
Smiling faces	365.6 (32.6)	343.7 (34.5)	286.1 (55.9)	368.2 (59.3)
Global local	83.5 (25.2)	61.8 (29.8)	87.9 (42.0)	118.9 (49.6)
TAP	0.91 (0.01)	0.93 (0.01)	0.93 (0.02)	0.94 (0.02)
UFoV-2	165.0 (18.6)	116.9 (14.8)	131.5 (30.8)	86.2 (24.4)
UFoV-3	276.1 (15.2)	261.5 (14.5)	273.3 (24.9)	208.3 (23.8)

See the main text for explanation of the indices.

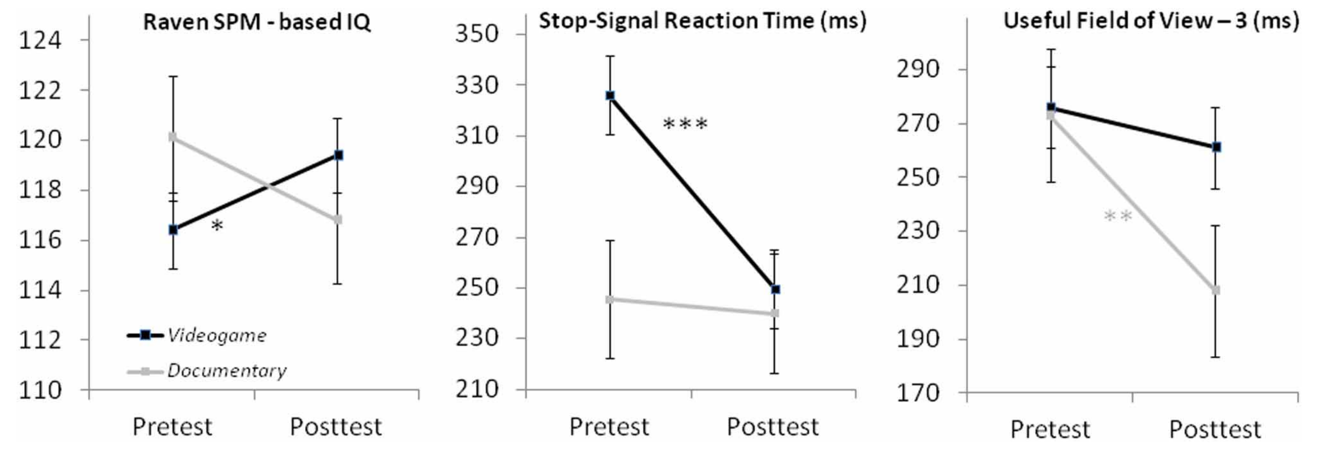

FIGURE 2 | Aggregate stop-signal RT, Raven IQ, and UFoV3 data at pre- and post-test in the game (black lines) and documentary (gray lines) condition. Significant changes in performance from pre- to post-test within each condition are indicated by asterisks. *$p = 0.05$, **$p < 0.05$, ***$p < 0.01$.

Table 4 | Significance of simple effects of time in each intervention condition.

Test	Condition	Statistic	Significance	Effect size (η_p^2)
Raven SPM	Game	$F_{(1, 51)} = 3.9$	$p = 0.05$	0.071
	Documentary	$F_{(1, 18)} = 2.7$	$p > 0.1$	0.128
Stop-signal	Game	$F_{(1, 38)} = 17.6$	$p < 0.001$	0.316
	Documentary	$F_{(1, 16)} < 1$	$p > 0.1$	0.004
UFoV-3	Game	$F_{(1, 50)} = 1.3$	$p > 0.1$	0.025
	Documentary	$F_{(1, 18)} = 10.4$	$p < 0.01$	0.367

*p*s > 0.2), indicating that there was no difference between men and women regarding the differential patterns of improvement of these cognitive functions in the videogame group and the documentary group.

Second, based on the patterns in the aggregate data, it could be argued that some of the significant interaction effects can be explained by anomalous performance at baseline in either one of the groups (Boot et al., 2011). To address this issue, *post-hoc t*-tests of the difference between the videogame and documentary condition regarding SSRT, Raven IQ, and UFoV-3 at pretest were performed. Only SSRT performance was significantly different between groups at pretest ($t_{(54)} = 2.4$, $p < 0.05$; other *p*s > 0.2). Because this SSRT analysis depended on a strict selection of participant performance, we looked for background differences between participant who had and those who had not been included in the analysis. There were no differences in age, MMSE, education, participation, gender composition, or Raven scores during pretest (all $p > 0.1$), so there is no reason to doubt whether the restricted sample is representative for the larger group.

DISCUSSION

The goal of the present study was to test whether playing online cognitive training games effectively benefits CC in a healthy elderly sample. An online cognitive training game intervention was compared to an intervention requiring participants to watch documentaries and answer quiz questions online. Based on the results of a similar study (Peretz et al., 2011) and ample evidence for far transfer of practicing basic cognitive tests to CC of older adults (Mahncke et al., 2006; Uchida and Kawashima, 2008; Karbach and Kray, 2009; Smith et al., 2009), far transfer of playing videogames to different measures of CC was expected. Transfer from the trained games to unrelated measures of CC was assessed using a cognitive test battery consisting of several tests of updating, shifting, and inhibition.

The improvement of Stop-Signal task and Raven-SPM performance was larger in the videogame group than in the documentary group. Simple effects analyses revealed that performance on neither of these tests improved in the documentary group, whereas the improvement of Stop-Signal task performance in the videogame group was significant and the improvement of Raven-SPM performance was marginally so. Based on these results, it can be concluded that playing cognitive training games online can transfer acquired skills to measures of inhibition and inductive reasoning. The sample under study consisted of relatively high functioning adults. Still, the improvement of Raven IQ entailed an average shift of participants in the videogame group from the 86th to the 90th percentile according to Peck's (1970) norms. The improvement of updating was small too, especially when compared to the extent of age-related decline of working memory (e.g., Baltes and Lindenberger, 1997). At first sight, the improvement of inhibition was substantial, especially in the context of Williams et al.'s (1999) finding that age predicts 5% of SSRT variance across individuals. So, even though inhibition declines with age (Coubard et al., 2011), it is possible to achieve improvements of inhibition on an individual level. This result thus provides evidence supporting the cognitive enrichment hypothesis (Hertzog et al., 2009).

The differential game effect on SSRT qualifies as an example of far transfer (Barnett and Ceci, 2002; Klingberg, 2010), because the videogames were mainly taxing updating, shifting, and inductive reasoning, but not inhibition. Note, however, that inhibition has been argued to form the core of CC. Friedman et al. (2008) performed a behavioral genetics study of CC that included separate measures of updating, switching, and inhibition. Inhibition had a 1.0 loading on the variance in CC, which implies that individual differences in inhibition abilities are closely related to what is common among CC functions.

The current study also, serendipitously, demonstrated a substantial improvement of selective attention in the documentary group, as measured by the UFoV-3, which was absent in the game group. This finding seems at odds with Green and Bavelier's (2003) observations that action videogame players processed more stimulus elements, across a larger visual angle, than non-videogame players. They also observed this difference in a randomized intervention study contrasting action games with Tetris. A tentative solution to this paradox is that a selective attention benefit occurs if an intervention challenges participants to monitor multiple stimuli simultaneously. This was the case in the documentary condition, where participants had to answer quiz questions about details in the documentary, but not in the game condition, as none of the games involved concurrent stimulus presentation. This interpretation is also in line with Green and Bavelier's account of their intervention results.

A critical note concerning the demonstration of transfer to inhibition is in place, however. The differential benefit of the game group for inhibition was partially due to differences between the groups that already existed prior to the intervention (cf. Boot et al., 2011), but that had faded following the intervention. Apparently, the substantial sample size and random assignment of participants had resulted in matched groups in terms of background characteristics, but had not led to sufficient matching of pre-test SSRT. Therefore, there is a risk that the effect of game training was overestimated, so it would be valuable if future studies of game effects could replicate this finding with groups that were matched on pre-test SSRT.

The transfer effects observed in the present study must be interpreted with caution for another reason as well. The current study explored several possible effects of game training. A conservative treatment of the data would therefore require the lowering of alpha to reduce the risk of a Type I error, for example by Bonferroni correction. None of the three interaction effects reported here would survive a Bonferroni correction for testing 10 hypotheses, which would lower the alpha to 0.005, although the simple effect of videogame training on the SSRT would be large enough to survive such an alpha level. The analyses are reported with an uncorrected alpha, however, because the literature on cognitive functions that show transfer of game training among older adults is still rather unexplored. In these circumstances, we find it equally important not to raise the risk of a Type II error.

Statistical shortcomings aside, the present results suggest that Owen et al.'s (2010) and Ackerman et al.'s (2010) negative conclusion regarding transfer of playing online brain training games to CC functions might not necessarily be correct. To a limited extent, the present findings support Basak et al.'s finding that inhibition can be improved by playing videogames and Schmiedek et al.'s (2010) demonstration that inductive reasoning can be improved by practicing basic cognitive tasks. The results from the present study suggest that modest improvements of inductive reasoning can also be achieved by means of playing cognitive training games. A similar partially positive result of games for CC and processing speed was reported by Nouchi et al. (2012).

At the same time, the absence of a benefit of videogame training for two measures of shifting, two measures of working memory span, and two measures of divided attention is reason not to be too optimistic about transfer of game training to higher cognitive functions. This is also the bottom line of the Owen et al. (2010) and Ackerman et al. (2010) studies. There are several points, however, in which the current study was better equipped than previous studies for demonstrating transfer effects of game training.

First, more than half of the participants in Ackerman et al.'s videogame intervention indicated that they did not enjoy playing the videogames. The low compliance to the videogame intervention in Owen et al.'s study also suggests that many participants did not find Owen et al.'s games very engaging either. In the present study, however, most of the participants in the videogame group indicated that they did enjoy playing the videogames. As suggested by Green and Bavelier (2008), motivation is a key condition for transfer to occur. The engaging nature of the videogames used in the present study could thus have facilitated transfer of training.

Second, the composition of the cognitive test battery that is used to assess transfer may confound the results of cognitive training studies. Owen et al.'s (2010) cognitive test battery, for instance, was restricted to no more than four tests. Owen et al. only obtained measures of updating and inductive reasoning, which may have obscured transfer to other cognitive domains as demonstrated in the present study. Ackerman et al. (2010) included a larger number of tests in their battery of transfer tests, but the test battery mainly comprised measures of perceptual speed and reasoning ability. As a consequence, transfer of training to inhibition, which was found in the present study, could have been overlooked in Ackerman et al.'s (2010) study. Interestingly, several measures of updating and inhibition were included in our test battery, but the positive effect of training on these CC functions could only be detected on one measure of the respective functions. Apparently, the reliability and validity of a cognitive test provides no guarantee for its sensitivity to transfer effects. It can be concluded that the approach of the current study to assess CC functions with an extensive cognitive test battery compensates for the possible insensitivity of some cognitive tests to transfer effects.

Third, the effect of a cognitive training intervention can be underestimated if the control intervention is too effective. The latter might have been the case in Owen et al.'s (2010) study. The control intervention required participants to search for answers to quiz questions on the internet. Participants could have employed and therefore practiced a wide range of strategies for finding answers to the questions. It is impossible to track whether this search caused participants to engage in other cognitively enriching activities. The current study demonstrated that the relatively inactive control condition, consisting of documentary viewing and answering quiz questions already resulted in improved selective attention. It is well possible that Owen et al.'s study presented participants in their control condition with at least the same amount of cognitive challenge.

Finally, not all videogames are created equal (Achtman et al., 2008) and given an individual's stage of cognitive development, one game can be more beneficial for cognitive functions than the other. For example, the cognitive training games used in the present study were very similar to those used in the ACTIVE study (Ball et al., 2002). Preliminary evidence for far transfer of cognitive training games was found in the present study but only near transfer was found in the ACTIVE study. The different extent of transfer in the ACTIVE study may be explained by the additional focus on learning to use specific strategies to perform the training tasks. Relying on a set of fixed strategies to cope with demands of a task at hand could have reduced the degree to which participants needed to exert CC during training. Thus, even though videogames of a similar genre were investigated in the present study and the ACTIVE study, a small difference between the intervention programs may be responsible for the different patterns of transfer that were observed.

In conclusion, the present study lends modest support to the notion that playing cognitive training games improves untrained CC functions in older adults. Since CC functions facilitate adaptive behavior in various contexts, improved CC can be expected to help older adults to overcome cognitive challenges in their daily routines. Videogames provide an entertaining and thus motivating tool for improving CC functions and they have other practical advantages as well. Videogames do not require physical well-being and mobility of the participant as much as physical exercise interventions, although these seem to be more effective in buffering decline of CC (cf. Colcombe and Kramer, 2003). Additionally, videogames are not expensive to administer as compared to interventions supervised by a therapist. Videogames come in forms far more complex than cognitive tests usually studied by cognitive psychologists. The present study suggests that the videogames should not be dismissed as a cognitive training tool, but that we are just beginning to understand how playing videogames influences cognitive functions.

Even within the homogeneous sample of older adults that participated in the present study, some participants benefited more from playing the videogames than others. A variety of factors may be responsible for individual differences in sensitivity to cognitive training. For instance, recent findings from our lab indicate that inter-individual genetic variability modulates transfer of training to untrained tasks (Colzato et al., 2011). Therefore, caution concerning the interpolation of aggregate data to individuals is advised, and individual differences in cognitive training outcomes are an important topic to be addressed in future studies.

The artwork of the games we presented here was not nearly as advanced and capturing as commercial off-the-shelf games, and that applies to most studies of game training. Conversely, commercial enhancement games are only seldom designed on the basis of cognitive insights, nor tested for their effectiveness. Given that the creative industry and academic research are only just starting to inspire each other's work, these first modest demonstrations of cognitive enhancement by games may only be scratching the surface of its full potential.

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REFERENCES

Achtman, R. L., Green, C. S., and Bavelier, D. (2008). Video games as a tool to train visual skills. *Restor. Neurol. Neurosci.* 26, 435–446.

Ackerman, P. L., Kanfer, R., and Calderwood, C. (2010). Use it or lose it? WII brain exercise practice and reading for domain knowledge. *Psychol. Aging* 25, 753–766.

Ball, K., Berch, D. B., Helmers, K. F., Jobe, J. B., Leveck, M. D., Marsiske, M., Morris, J. N., Rebok, G. W., Smith, D. M., Tennstedt, S. L., Unverzagt, F. W., and Willis, S. L. (2002). Effects of cognitive training interventions with older adults: a randomized controlled trial. *JAMA* 288, 2271–2281.

Ball, K., Edwards, J. D., and Ross, L. A. (2007). The impact of speed of processing training on cognitive and everyday functions. *J. Gerontol. B Psychol. Sci. Soc. Sci.* 62, 19–31.

Baltes, P. B., and Lindenberger, U. (1997). Emergence of a powerful connection between sensory and cognitive functions across the adult life span: a new window to the study of cognitive aging? *Psychol. Aging* 12, 12–21.

Band, G. P., Van Der Molen, M. W., and Logan, G. D. (2003). Horse-race model simulations of the stop-signal procedure. *Acta Psychol. (Amst.)* 112, 105–142.

Barnett, S. M., and Ceci, S. J. (2002). When and where do we apply what we learn? A taxonomy for far transfer. *Psychol. Bull.* 128, 612–637.

Baron, A., and Mattila, W. R. (1989). Response slowing of older adults: effects of time-limit contingencies on single- and dual-task performances. *Psychol. Aging* 4, 66–72.

Basak, C., Boot, W. R., Voss, M. W., and Kramer, A. F. (2008). Can training in a real-time strategy video game attenuate cognitive decline in older adults? *Psychol. Aging* 23, 765–777.

Bherer, L., Kramer, A. F., Peterson, M. S., Colcombe, S., Erickson, K., and Becic, E. (2008). Transfer effects in task-set cost and dual-task cost after dual-task training in older and younger adults: further evidence for cognitive plasticity in attentional control in late adulthood. *Exp. Aging Res.* 34, 188–219.

Boot, W. R., Blakely, D. P., and Simons, D. J. (2011). Do action video games improve perception and cognition? *Front. Psychol.* 2:226. doi: 10.3389/fpsyg.2011.00226

Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., and Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychol. Rev.* 108, 624–652.

Burgess, P. W., Alderman, N., Evans, J., Emslie, H., and Wilson, B. A. (1998). The ecological validity of tests of executive function. *J. Int. Neuropsychol. Soc.* 4, 547–558.

Buschkuehl, M., Jaeggi, S. M., Hutchison, S., Perrig-Chiello, P., Dapp, C., Muller, M., Breil, F., Hoppeler, H., and Perrig, W. J. (2008). Impact of working memory training on memory performance in old-old adults. *Psychol. Aging* 23, 743–753.

Cohen, J. (1992). A power primer. *Psychol. Bull.* 112, 155–159.

Colcombe, S., and Kramer, A. F. (2003). Fitness effects on the cognitive function of older adults: a meta-analytic study. *Psychol. Sci.* 14, 125–130.

Colzato, L. S., Van Muijden, J., Band, G. P. H., and Hommel, B. (2011). Genetic modulation of training and transfer in older adults: BDNF Val66Met polymorphism is associated with wider useful field of view. *Front. Psychol.* 2:199. doi: 10.3389/fpsyg.2011.00199

Conway, A. R., Kane, M. J., and Engle, R. W. (2003). Working memory capacity and its relation to general intelligence. *Trends Cogn. Sci.* 7, 547–552.

Coubard, O. A., Ferrufino, L., Boura, M., Gripon, A., Renaud, M., and Bherer, L. (2011). Attentional control in normal aging and Alzheimer's disease. *Neuropsychology* 25, 353–367.

Dahlin, E., Neely, A. S., Larsson, A., Backman, L., and Nyberg, L. (2008). Transfer of learning after updating training mediated by the striatum. *Science* 320, 1510–1512.

Davidson, D. J., Zacks, R. T., and Williams, C. C. (2003). Stroop interference, practice, and aging. *Neuropsychol. Dev. Cogn. B Aging Neuropsychol. Cogn.* 10, 85–98.

Denney, N. W. (1984). A model of cognitive-development across the life-span. *Dev. Rev.* 4, 171–191.

Dustman, R. E., Emmerson, R. Y., Steinhaus, L. A., Shearer, D. E., and Dustman, T. J. (1992). The effects of videogame playing on neuropsychological performance of elderly individuals. *J. Gerontol.* 47, P168–P171.

Edwards, J. D., Ross, L. A., Wadley, V. G., Clay, O. J., Crowe, M., Roenker, D. L., and Ball, K. K. (2006). The useful field of view test: normative data for older adults. *Arch. Clin. Neuropsychol.* 21, 275–286.

Edwards, J. D., Wadley, V. G., Vance, D. E., Wood, K., Roenker, D. L., and Ball, K. K. (2005). The impact of speed of processing training on cognitive and everyday performance. *Aging Ment. Health* 9, 262–271.

Ericsson, K. A., Krampe, R. T., and Tesch-Römer, C. (1993). The role of deliberate practice in the acquisition of expert performance. *Psychol. Rev.* 100, 363–406.

Feng, J., Spence, I., and Pratt, J. (2007). Playing an action video game reduces gender differences in spatial cognition. *Psychol. Sci.* 18, 850–855.

Fisk, J. E., and Sharp, C. A. (2004). Age-related impairment in executive functioning: updating, inhibition, shifting, and access. *J. Clin. Exp. Neuropsychol.* 26, 874–890.

Folstein, M. F., Folstein, S. E., and Mchugh, P. R. (1975). "Mini-mental state". A practical method for grading the cognitive state of patients for the clinician. *J. Psychiatr. Res.* 12, 189–198.

Friedman, N. P., Miyake, A., Young, S. E., Defries, J. C., Corley, R. P., and Hewitt, J. K. (2008). Individual differences in executive functions are almost entirely genetic in origin. *J. Exp. Psychol. Gen.* 137, 201–225.

Gee, J. P. (2007). *What Video Games Have to Teach Us About Learning and Literacy*. New York, NY: Palgrave Macmillan.

Green, C. S., and Bavelier, D. (2003). Action video game modifies visual selective attention. *Nature* 423, 534–537.

Green, C. S., and Bavelier, D. (2008). Exercising your brain: a review of human brain plasticity and training-induced learning. *Psychol. Aging* 23, 692–701.

Hertzog, C., Kramer, A. F., Wilson, R. S., and Lindenberger, U. (2009). Enrichment effects on adult cognitive development: can the functional capacity of older adults be preserved and enhanced? *Psychol. Sci. Public Interest* 9, 1–65.

Huizinga, M., Dolan, C. V., and Van Der Molen, M. W. (2006). Age-related change in executive function: developmental trends and a latent variable analysis. *Neuropsychologia* 44, 2017–2036.

Karbach, J., and Kray, J. (2009). How useful is executive control training? Age differences in near and far transfer of task-switching training. *Dev. Sci.* 12, 978–990.

Keizer, A. W., Verschoor, M., Verment, R. S., and Hommel, B. (2010). The effect of gamma enhancing neurofeedback on the control of feature bindings and intelligence measures. *Int. J. Psychophysiol.* 75, 25–32.

Klingberg, T. (2010). Training and plasticity of working memory. *Trends Cogn. Sci.* 14, 317–324.

Kramer, A. F., Humphrey, D. G., Larish, J. F., Logan, G. D., and Strayer, D. L. (1994). Aging and inhibition: beyond a unitary view of inhibitory processing in attention. *Psychol. Aging* 9, 491–512.

Kray, J., Eber, J., and Karbach, J. (2008). Verbal self-instructions in task switching: a compensatory tool for action-control deficits in childhood and old age? *Dev. Sci.* 11, 223–236.

Kray, J., and Lindenberger, U. (2000). Adult age differences in task switching. *Psychol. Aging* 15, 126–147.

Larson, G. E., and Saccuzzo, D. P. (1989). Cognitive correlates of general intelligence - toward a process theory of G. *Intelligence* 13, 5–31.

Lindenberger, U., and Ghisletta, P. (2009). Cognitive and sensory declines in old age: gauging the evidence for a common cause. *Psychol. Aging* 24, 1–16.

Logan, G. D. (1988). Automaticity, resources, and memory: theoretical controversies and practical implications. *Hum. Factors* 30, 583–598.

Logan, G. D., Cowan, W. B., and Davis, K. A. (1984). On the ability to inhibit simple and choice reaction time responses: a model and a method. *J. Exp. Psychol. Hum. Percept. Perform.* 10, 276–291.

Macdonald, S. W., Hultsch, D. F., and Dixon, R. A. (2011). Aging and the shape of cognitive change before death: terminal decline or terminal drop? *J. Gerontol. B Psychol. Sci. Soc. Sci.* 66, 292–301.

Mahncke, H. W., Connor, B. B., Appelman, J., Ahsanuddin, O. N., Hardy, J. L., Wood, R. A., Joyce, N. M., Boniske, T., Atkins, S. M., and Merzenich, M. M. (2006). Memory enhancement in healthy older adults using a brain plasticity-based training program: a randomized, controlled study. *Proc. Natl. Acad. Sci. U.S.A.* 103, 12523–12528.

Majer, M., Ising, M., Kunzel, H., Binder, E. B., Holsboer, F., Modell, S., and Zihl, J. (2004). Impaired divided attention predicts delayed response and risk to relapse in subjects with depressive disorders. *Psychol. Med.* 34, 1453–1463.

Mayr, U., Kliegl, R., and Krampe, R. T. (1996). Sequential and coordinative processing dynamics in figural transformations across the life span. *Cognition* 59, 61–90.

Meijer, W. A., Van Boxtel, M. P., Van Gerven, P. W., Van Hooren, S. A., and Jolles, J. (2009). Interaction effects of education and health status on cognitive change: a 6-year follow-up of the Maastricht Aging Study. *Aging Ment. Health* 13, 521–529.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., and Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "Frontal Lobe" tasks: a latent variable analysis. *Cogn. Psychol.* 41, 49–100.

Nouchi, R., Taki, Y., Takeuchi, H., Hashizume, H., Akitsuki, Y., Shigemune, Y., Sekiguchi, A., Kotozaki, Y., Tsukiura, T., Yomogida, Y., and Kawashima, R. (2012). "Brain training game improves executive functions and processing speed in the elderly". *PLoS ONE* 7:e29676. doi: 10.1371/journal.pone.0029676

Owen, A. M., Hampshire, A., Grahn, J. A., Stenton, R., Dajani, S., Burns, A. S., Howard, R. J., and Ballard, C. G. (2010). Putting brain training to the test. *Nature* 465, 775–778.

Peck, D. F. (1970). The conversion of Progressive Matrices and Mill Hill Vocabulary raw scores into deviation IQ's. *J. Clin. Psychol.* 26, 67–70.

Peretz, C., Korczyn, A. D., Shatil, E., Aharonson, V., Birnboim, S., and Giladi, N. (2011). Computer-based, personalized cognitive training versus classical computer games: a randomized double-blind prospective trial of cognitive stimulation. *Neuroepidemiology* 36, 91–99.

Posner, M. I., and DiGirolamo, G. J. (1998). "Executive attention: conflict, target detection and cognitive control," in *The Attentive Brain*, ed R. Parasuraman (Cambridge, MA, US: The MIT Press), 401–423.

Raven, J. C. (1938). *Progressive Matrices: A Perceptual Test of Intelligence*. London, UK: H. K. Lewis.

Salthouse, T. A., Atkinson, T. M., and Berish, D. E. (2003). Executive functioning as a potential mediator of age-related cognitive decline in normal adults. *J. Exp. Psychol. Gen.* 132, 566–594.

Salthouse, T. A., Fristoe, N., McGuthry, K. E., and Hambrick, D. Z. (1998). Relation of task switching to speed, age, and fluid intelligence. *Psychol. Aging* 13, 445–461.

Sammer, G., Reuter, I., Hullmann, K., Kaps, M., and Vaitl, D. (2006). Training of executive functions in Parkinson's disease. *J. Neurol. Sci.* 248, 115–119.

Schmidt, R. A., and Bjork, R. A. (1992). New conceptualizations of practice. Common principles in three paradigms suggest new concepts for training. *Psychol. Sci.* 3, 207–217.

Schmiedek, F., Hildebrandt, A., Lovden, M., Lindenberger, U., and Wilhelm, O. (2009). Complex span versus updating tasks of working memory: the gap is not that deep. *J. Exp. Psychol. Learn. Mem. Cogn.* 35, 1089–1096.

Schmiedek, F., Lovden, M., and Lindenberger, U. (2010). Hundred days of cognitive training enhance broad cognitive abilities in adulthood: findings from the COGITO study. *Front. Aging Neurosci.* 2:27. doi: 10.3389/fnagi.2010.00027

Shiffrin, R. M., and Schneider, W. (1977). Controlled and automatic human information processing: II. Perceptual learning, automatic attending and a general theory. *Psychol. Rev.* 84, 127–190.

Singer, T., Lindenberger, U., and Baltes, P. B. (2003). Plasticity of memory for new learning in very old age: a story of major loss? *Psychol. Aging* 18, 306–317.

Smith, G. E., Housen, P., Yaffe, K., Ruff, R., Kennison, R. F., Mahncke, H. W., and Zelinski, E. M. (2009). A cognitive training program based on principles of brain plasticity: results from the improvement in Memory with Plasticity-based Adaptive Cognitive Training (IMPACT) study. *J. Am. Geriatr. Soc.* 57, 594–603.

Span, M. M., Ridderinkhof, K. R., and Van Der Molen, M. W. (2004). Age-related changes in the efficiency of cognitive processing across the life span. *Acta Psychol. (Amst.)* 117, 155–183.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *J. Exp. Psychol.* 18, 643–662.

Tucker-Drob, E. M. (2011). Neurocognitive functions and everyday functions change together in old age. *Neuropsychology* 25, 368–377.

Uchida, S., and Kawashima, R. (2008). Reading and solving arithmetic problems improves cognitive functions of normal aged people: a randomized controlled study. *Age (Dordr.)* 30, 21–29.

United-Nations, (2010). *World Population Aging 2009* [Online]. United Nations publication. Available online at: http://www.un.org/esa/population/publications/WPA2009/WPA2009-report.pdf (Accessed 30 August 2011).

Wild-Wall, N., Hahn, M., and Falkenstein, M. (2011). Preparatory processes and compensatory effort in older and younger participants in a driving-like dual task. *Hum. Factors* 53, 91–102.

Williams, B. R., Ponesse, J. S., Schachar, R. J., Logan, G. D., and Tannock, R. (1999). Development of inhibitory control across the life span. *Dev. Psychol.* 35, 205–213.

Zelazo, P. D., Craik, F. I., and Booth, L. (2004). Executive function across the life span. *Acta Psychol. (Amst.)* 115, 167–183.

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Training the developing brain: a neurocognitive perspective

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Developmental training studies are important to increase our understanding of the potential of the developing brain by providing answers to questions such as: "Which functions can and which functions cannot be improved as a result of practice?," "Is there a specific period during which training has more impact?," and "Is it always advantageous to train a particular function?" In addition, neuroimaging methods provide valuable information about the underlying mechanisms that drive cognitive plasticity. In this review, we describe how neuroscientific studies of training effects inform us about the possibilities of the developing brain, pointing out that childhood is a special period during which training may have different effects. We conclude that there is much complexity in interpreting training effects in children. Depending on the type of training and the level of maturation of the individual, training may influence developmental trajectories in different ways. We propose that the immature brain structure might set limits on how much can be achieved with training, but that the immaturity can also have advantages, in terms of flexibility for learning.

Keywords: training, development, executive functions, cognitive control, plasticity, neuroimaging, brain maturation

INTRODUCTION

The human brain is highly plastic and adapts quickly to new experiences. Several examples are at hand that highlight the plasticity of the brain in adults. For instance, a famous set of studies with London taxi drivers suggested that the gray matter volume in the hippocampus, a region important for memory, can be modulated by training. Moreover, these studies showed that hippocampal gray matter volume corresponded with the level of driving experience (Maguire et al., 2000, 2006) (see e.g., Elbert et al., 1995; Gaser and Schlaug, 2003 for similar results in musicians). Besides brain structure, also the function of the brain can be influenced by training. There is evidence from studies showing altered brain activation in limbic and/or frontoparietal regions for long-term meditation practitioners (Brefczynski-Lewis et al., 2007; Lutz et al., 2008) and after training with working memory tasks (Olesen et al., 2004; Jolles et al., 2010; Klingberg, 2010). It is well known that much of our learning takes place in childhood. But what do we know about the plasticity and flexibility of the developing brain? How can neuroscientific studies increase our insight of training effects during development?

In this article, we suggest that childhood might be special period during which training has specific effects. Currently, relatively little is known about how training-related plasticity differs between children and adults, but this direction of research has great potential for tailoring optimal learning situations. On the one hand, there are great changes in neural efficiency during development, which could make this period well suited for training interventions. On the other hand, there might also be limitations on the effects of training in childhood. That is, the maximum achievable performance could be constrained by the current level of structural brain development and cognitive functioning. Neuroimaging studies can provide a deeper level of insight in the underlying cognitive and neural processes that are involved during training (cf. Lustig et al., 2009). In this review, we mainly focus on (neuroscientific) training studies in the domain of cognitive control and working memory. In adults, these functions are associated with activation in a common set of regions in prefrontal and parietal cortex (Duncan and Owen, 2000; Wager and Smith, 2003; Owen et al., 2005). Several behavioral studies have demonstrated improved performance after cognitive training in children, and there is now a growing interest in the changes in frontoparietal brain regions that accompany these behavioral changes.

In the following sections, we first give a general introduction about the aims and methods of cognitive training studies, based on the child and adult behavioral literature. Then, we provide background on the interplay between brain maturation and training effects. Finally, we discuss the results of the first neuroscientific training studies in children. We conclude with some critical considerations and directions for future research.

COGNITIVE TRAINING: PURPOSE AND APPROACH

TRAINING PARADIGMS

In this article, cognitive training is defined as the process of improving cognitive functioning by means of practice and/or intentional instruction. For alternative approaches to improve cognitive functions, including ecological interventions, physical exercise, and social interaction, we refer to previous reviews of cognitive interventions in children (Diamond and Lee, 2011; Bryck and Fisher, 2012) and adults (Hertzog et al., 2009; Lustig et al., 2009; Noack et al., 2009; Buschkuehl and Jaeggi, 2010). In general, cognitive training studies have focused on two goals: application (i.e., designing a training intervention that is effective in practice), and theory (i.e., answering empirical questions about the functions that are being trained and the processes responsible for the desired change) (Willis and Schaie, 2009). While determining the efficacy of a training program is a key objective in most training studies, it is equally important that training studies provide new insights into the processes of cognitive plasticity and the underlying neural mechanisms. For example, theory-based training studies may help to determine which aspects of the training program are driving training effects, and why some individuals gain more from training than others. In addition, theory-based training studies can improve our understanding of the specific functions that are being trained and why these functions are sometimes compromised (Willis and Schaie, 2009).

Depending on the goals of the study, a variety of different training paradigms can be used. The major approaches of cognitive training can roughly be classified as process-based and strategy-based training paradigms (cf. Lustig et al., 2009; Noack et al., 2009; Morrison and Chein, 2010). The process-based approach involves repeated performance (i.e., practice) of demanding executive function tasks. Most process-based studies in children have focused on training of working memory (e.g., Klingberg et al., 2005; Holmes et al., 2009a; Van der Molen et al., 2010; Jaeggi et al., 2011; Jolles et al., 2012), but other functions have been studied as well, including (executive) attention (e.g., Rueda et al., 2005; Shalev et al., 2007), inhibition (e.g., Thorell et al., 2009; Johnstone et al., 2010), and task switching (e.g., Karbach and Kray, 2009). The strategy-based approach on the other hand uses more explicit task instructions. For instance, in the domain of working memory, strategy training studies have promoted the use of rehearsal, chunking, mental imagery, and/or story-formation strategies to increase the number of items that are held in mind (e.g., Ford et al., 1984; Conners et al., 2008; St. Clair-Thompson et al., 2010; Swanson et al., 2010). Other strategy-based studies have used a more general approach, providing metacognitive knowledge about controlling and regulating task procedures and strategies (e.g., Ghatala et al., 1985; Kramarski and Mevarech, 2003). While it has been argued that process-based training of core executive functions will show a broader generalization because it is more domain-general in nature (cf. Lustig et al., 2009; Noack et al., 2009; Klingberg, 2010; Morrison and Chein, 2010), the strategy-based approach might be specifically effective in studies that aim to improve a particular skill (e.g., in arithmetic or language). Interestingly, in a study of children with attention difficulties, both typical process-based attention training and training of academic skills (which involved strategy-based elements) reduced attention problems. However, only the children who took part in the academic training improved significantly on (some) academic skills (Rabiner et al., 2010). Finally, a number of studies have explored the combination of process-based training and strategy instructions (van't Hooft et al., 2003, 2005; Chenault et al., 2006). One of these studies demonstrated that children with dyslexia benefit more from writing instruction when this is preceded by process-based training of attention, than when it is preceded by a control training (reading fluency). Notably, the attention training itself did not directly improve writing skills; it was the combination of training programs that yielded the best results (Chenault et al., 2006). These findings indicate that the process-based attention training facilitated learning during the writing lessons, demonstrating the potential benefit of combining process-based and strategy-based training procedures.

Except from the process-based versus strategy-based distinction, there are several other factors that should be considered when designing a training study, including the length of the training, the complexity of the task that is trained (i.e., does the task train one specific function or several different processes at once), the variability in stimuli and tasks (both within and between cognitive domains), and whether or not the difficulty level of the trained task(s) is adapted to the participants' level of performance. These factors depend strongly on the goal of the study (e.g., theory versus application). For instance, a study that examines theoretical questions about training-related changes in cognitive processes will benefit most from a simple training paradigm that controls for confounding variables (cf. Luna et al., 2010; Morrison and Chein, 2010). However, a study that aims to develop a cognitive intervention that is effective in practice might benefit more from a complex training paradigm. It has been suggested that training with complex and variable tasks will lead to greater generalization to real-life situations (Green and Bavelier, 2008; Lustig et al., 2009; Buschkuehl and Jaeggi, 2010). In addition, changing stimuli and adapting the difficulty level of the task are considered important methods to keep the participant motivated and to prevent automaticity (Green and Bavelier, 2008; Buschkuehl and Jaeggi, 2010; Klingberg, 2010; Morrison and Chein, 2010). There have only been a small number of studies in children that directly examined the influence of these factors and definitive conclusions have not yet been reached. For example, a number of studies have demonstrated that adaptive training led to greater training effects than non-adaptive training (Klingberg et al., 2002, 2005; Holmes et al., 2009a; Bergman Nutley et al., 2011; but see also Van der Molen et al., 2010), yet most of these studies used non-adaptive training with a very low difficulty. It is unclear whether adaptive training is still more successful than non-adaptive training if the latter is more challenging, and if so, what would be the optimal level of task difficulty to facilitate learning. In addition, the few studies that directly examined the effects of task variability did not find clear evidence that training with variable tasks will lead to greater generalization. For example, Karbach and Kray (2009) demonstrated that children who trained with different versions of the same task showed *less* transfer of training gain than children who trained with only one version. These findings were opposite of the findings in adults, who showed larger transfer effects in the variable training condition (Karbach and Kray, 2009). Furthermore, to examine whether generalizability would be larger for a training program that encompasses several cognitive domains than for training that is focused on one domain, Bergman Nutley et al. (2011) studied the effects of training both working memory and non-verbal reasoning relative to training only one of these functions. They demonstrated that the improvement on the specific functions was roughly proportionate to the amount of training in that particular domain, and there was no evidence of enhanced generalization if training was divided between cognitive domains. Future studies should further examine "success factors" (i.e., characteristics of the training paradigm that promote training gain and generalizability) and determine to which extent these factors are age-dependent.

ASSESSING TRAINING EFFECTIVENESS: DEPENDENT VARIABLES

There are several ways to determine the effectiveness of the training, the most obvious being performance improvements (e.g., in accuracy or response times) on the trained task. Additional variables that could be studied include the frequency of a particular strategy that is employed, as well as the speed or proficiency with which that strategy is used (Willis and Schaie, 2009). If performance is measured throughout the training period, it is also possible to estimate a learning curve, which shows how the learning rate changes over time. Typically, the learning curve is steep at the beginning of training, but gradually becomes more flat when learning progresses (e.g., Jolles et al., 2010; Van der Molen et al., 2010; Loosli et al., 2011). The decreasing slope of performance improvements can partly be explained by the different aspects of the task that are being trained. For example, in the beginning of the training, participants might adopt a new strategy that improves performance dramatically. Later in training, performance improvements often slow down because participants are simply practicing with the same strategy over and over again. Moreover, in the beginning of training, a number of additional factors are introduced that are not directly related to the trained function of interest, including the equipment, the experimenter, and other aspects of the training context. Getting used to these extraneous factors contributes to the steep learning curve in the beginning of training. It is important to note that the learning curves of individual participants do not necessarily take the same form as the average curve of the group (Heathcote et al., 2000). Especially if there is a large variability in learning rate, the average learning curve of the group can be distorted, which suggests that individual curves should always be taken into account. Moreover, when comparing performance improvements between groups (e.g., children versus adults or children with developmental disabilities versus typically developing children), it is important to pay attention to performance differences before and after the training, as well as the room for improvement. Because it seems that performance improvements slow down when there is less room for improvement, the group that is closest to asymptotic performance will show less performance gains. In addition, it is possible that one group shows a larger improvement, while their maximal performance is still below that of the other group.

Besides performance improvements during the training, it is informative to examine the long-term effects of training, using a follow-up measurement several months after the training is completed (e.g., Klingberg et al., 2005; Holmes et al., 2009b; Beck et al., 2010; Jolles et al., 2010; Jaeggi et al., 2011). This follow-up test does not only examine the durability of training effects, but also tests for cumulative effects. That is, training gains may be enhanced during the follow-up test as a result of the secondary effects of training, including increased motivation or ability to learn. Some of these secondary effects (such as better school performance) require some time to establish (Holmes et al., 2009a; Van der Molen et al., 2010).

To rule out test-retest effects (e.g., Bors and Vigneau, 2001; Goodyear and Douglas, 2009; Jolles et al., 2010), it is important to compare the performance of the trained participants to that of a control group who did not participate in the training. Several studies have used a passive control group, which only participated in the pre- and posttraining sessions. Although a passive control group is useful to rule out the effects of familiarity, it does not take into account expectancy effects and motivation (see **Box 1**). To control for these effects, an active control group should be included, which receives a "placebo treatment". Several placebo interventions have been proposed, including training the same task at a low difficulty (e.g., Klingberg et al., 2005; Holmes et al., 2009a; Bergman Nutley et al., 2011), watching videos (Rueda et al., 2005), and playing computer games (Shalev et al., 2007; Thorell et al., 2009). Yet, a control treatment is difficult to design because it should be very similar to the training program, but it must not be effective. Therefore, an alternative approach is to compare the effects of two training programs that focus on different cognitive functions (Thorell et al., 2009; Mackey et al., 2011).

A critical aspect to assess the generalizability of training benefits is the transfer of training effects to untrained tasks and real-life situations. Several studies have demonstrated near transfer of training effects to tasks within the same domain (e.g., Holmes et al., 2009b; Bergman Nutley et al., 2011; Mackey et al., 2011), and a number of studies have even found transfer to other domains, academic performance measures, or symptoms of inattention and hyperactivity (e.g., Klingberg et al., 2005; Rueda et al., 2005; Karbach and Kray, 2009; Dahlin, 2011; Loosli et al., 2011). However, transfer effects are highly inconsistent across studies, and the exact variables that lead to the transfer effects are still unclear. Perhaps this is due to the majority of studies focusing on the efficacy of the training, rather than *why* the training is effective, and *what* exactly is being transferred (Willis and Schaie, 2009). Yet, transfer effects are not only important from an intervention perspective. They can inform us about the underlying cognitive processes that change as a result of training. This is even important if one well-described task is being trained. Because of the "impurity" of executive function tasks (Miyake et al., 2000; Huizinga et al., 2006), there are many processes that can be influenced by training. For instance, if participants practice with a working memory task, training may lead to a general increase in processing efficiency (e.g., an increase of working memory capacity), a strategy change (e.g., the use of rehearsal to memorize items in working memory), or a task-specific skill (e.g., familiarity with the memory items). These processes can be disentangled if the participants also perform a number of transfer tasks that have one or more elements in common with the trained task. The use of a latent-variable approach can be particularly fruitful in this respect (Noack et al., 2009; Schmiedek et al., 2010; Bergman Nutley et al., 2011).

Box 1 | Confounding factors.

It seems that there is a multitude of possible cognitive and neural processes that underlie the observed training effects, and it is likely that these processes differ between children and adults. The interpretation of training effects is further complicated by several confounding factors. Here, we briefly summarize the most important confounding factors and some remedies (see also Poldrack, 2000; Church et al., 2010; Galvan, 2010; Morrison and Chein, 2010):

General confounding factors

- Familiarity: training effects could reflect test-retest effects, rather than true improvements on the variables of interest.
- Expectancy effects (comparable to placebo effects in drug studies): participants might improve simply because of increased confidence or because they put in more effort after training.
- Shared components between the context of the trained task and transfer task: improvement on the transfer tasks might be related to familiarity with type of task or stimuli, rather than training-related changes in the underlying processes.
- Motivation, feedback, and rewards: the value of feedback and rewards might differ between groups, suggesting that one group might be more motivated than another. Motivation also depends on task difficulty. That is, the training is expected to be most encouraging when the task is not too easy and not too difficult.
- Cohort effects: group differences might be related to other factors than the factor of interest alone. For example, familiarity with computer games likely differs between children and aduls, which could influence learning rate if the training is computer-based.

Factors specific to neuroimaging

- Task performance: changes of neural activity may be related to difficulty, effort, or reduced time on task, rather than changes of the process of interest.
- Task irrelevant processing: with increased performance, there might be more time for mind wandering, which is often associated with increased activation in the so-called "default mode network" (e.g., Raichle et al., 2001; Buckner et al., 2008).
- The task B problem: neuroimaging studies often compare activation during a condition of interest (Task A), with a control condition (Task B). Therefore, training effects might be confounded with activation changes in the control condition.
- Awareness of task: activation changes might be due to increased awareness of, for example, the task structure.
- Morphological changes: activation changes might be affected by changes in the underlying brain structure.
- Scanner anxiety: when participants are scanned for the second time, they are often less anxious, which could have direct and indirect (e.g., reduced head movement) effects on BOLD activity.
- Performance of the scanner: activity changes could be influenced by scanner instability, which may affect the signal-to-noise ratio.

Remedies

Some issues are not as problematic as others, i.e., if they influence all conditions/groups evenly. In other cases, it is important to gather information about the possible confounding factors and, if possible, control for these factors. Here, we provide some recommendations to explore/control for confounding factors:

- Monitor strategy use, motivation, effort, and scanner anxiety
- Reduce scanner anxiety by using a mock scanner
- Use a parametric modulation of task difficulty or vary one aspect of the task to keep task difficulty similar across conditions/groups
- Use transfer tasks to better understand the underlying processes
- Use an active control group to monitor familiarity, expectancy, and motivation
- Include covariates in the analysis. For instance, in the fMRI analysis, grey matter can be included as a voxelwise regressor to take into account the gray matter changes after training and/or changes in registration error.

TRAINING EFFECTS IN THE CONTEXT OF THE DEVELOPING BRAIN

Children can improve their performance on cognitive control tasks as a result of training. This has been demonstrated both in healthy children (e.g., Karbach and Kray, 2009; Thorell et al., 2009; St. Clair-Thompson et al., 2010; Bergman Nutley et al., 2011; Loosli et al., 2011), and in children with cognitive or attentional impairments (e.g., Klingberg et al., 2005; Shalev et al., 2007; Bangirana et al., 2009; Holmes et al., 2009a; Mezzacappa and Buckner, 2010; Rabiner et al., 2010; Van der Molen et al., 2010). However, what does it mean if children reach more "mature" levels of performance, or if children with a developmental disability show "normalized" performance after training (cf. Karmiloff-Smith, 2009)? There are a few factors that should be taken into account, including the sensitivity and the ecological validity of the test, and the underlying processes that might be involved. That is, comparable test scores between groups do not necessarily mean that the groups use the same underlying cognitive processes and brain networks. Neuroscientific methods may add to this discussion by giving insight in the underlying mechanisms of cognitive plasticity and the relation between training effects and brain development.

According to Johnson (2001, 2011), there are three different viewpoints within the field of developmental cognitive neuroscience. First, the maturational viewpoint suggests that cognitive functions develop when the underlying brain regions reach maturity. In contrast, the second viewpoint, the interactive specialization account, suggests that the specialization of a particular brain region is a consequence of its interaction and competition with other brain regions over the course of development. This viewpoint has probably received the most support, as it takes into account the role of experience in brain maturation, suggesting that general rules of structural development might be genetically programmed, but specific details are the result of activity-dependent processes influenced by the environment (Changeux and Danchin, 1976; Greenough et al., 1987; Huttenlocher, 2002; Uylings, 2006). This account also points out that brain regions should always be viewed in relation to the functional networks in which they are involved. The third viewpoint is the skill-learning account, which emphasizes that the patterns of change observed during development are sometimes similar to those involved in skill acquisition in adults (Johnson, 2001; Casey et al., 2005; Johnson, 2011). This account argues that it is important to distinguish between the effects of age and performance in driving differences in brain activation between children and adults. Together, these viewpoints may be used to describe the effects of training in the developing brain.

In the following paragraphs, we describe three questions that are of particular importance when studying the effects of training in children and how these relate to the different viewpoints.

1. How are training effects influenced by the current stage of development?

Over the course of development, the human brain undergoes dramatic changes, driven by a series of progressive (e.g., myelination and strengthening of synapses) and regressive events (e.g., selective pruning of neurons and synaptic connections; e.g., Uylings, 2006; Stiles, 2008; Giedd and Rapoport, 2010). It is expected that the same training will have different outcomes in children and adults, depending on the nature of the function that is trained, and the brain structures and neuronal networks in which the changes take place (cf. Galvan, 2010; Kolb et al., 2010). While training in adults mainly modifies the existing neural architecture, in young children it may still influence the construction of neural networks (cf. Galvan, 2010), suggesting that there are both quantitatively and qualitatively different effects of training in children and adults.

On the one hand, an immature brain structure might set limits on how much can be achieved with practice. For example, the speed and efficiency of information processing are determined by the degree of myelination, and the pattern of synaptic connectivity (Goldman-Rakic, 1987; Chechik et al., 1998; Fields, 2008; Paus, 2010). This could, for instance, constrain practice-related gains on speeded control tasks or working memory (e.g., Case et al., 1982). Besides, training gains are limited by the stage of cognitive development (and thus by age and earlier experience). That is, a child cannot learn new skills if these skills build upon more primitive processes that are not yet mature (Zelazo, 2004). Thus, it is likely that there are particular cognitive processes that cannot be accelerated with training interventions. Therefore, it is expected that some age differences are actually magnified rather than reduced after training, which has also been demonstrated in training studies examining younger versus older adults (Baltes and Kliegl, 1992; Nyberg et al., 2003).

On the other hand, it has been suggested that in some cases, immaturity is actually advantageous (Ramscar and Gitcho, 2007; Bjorklund et al., 2009). For example, it has been argued that increasing specialization and integration in brain networks over the course of development goes at the expense of plasticity (Huttenlocher, 2003; Johnson, 2011). Or, as Thompson-Schill et al. (2009) put it: “a system optimized for performance may not be optimal for learning, and vice versa” (p. 260). Moreover, it has been suggested that there are “sensitive periods” in brain development during which specific experiences have their largest effects. Sensitive periods are most pronounced for basic sensory processes that occur during the first years of life, and they are expected to coincide with periods in which there is an abundance of neurons, axonal projections, and synaptic connections (Greenough et al., 1987; Huttenlocher, 2002; Uylings, 2006). With respect to higher cognitive functions, there is still a debate about the existence of sensitive periods. Because of the flexible nature of higher cognitive functions, these functions probably rely on neural mechanisms with life-long plasticity. Nevertheless, it is possible that the capacity for plasticity becomes smaller with age because of the increasing specificity of brain function (cf. Huttenlocher, 2003; Uylings, 2006; Johnson, 2011).

Finally, without denying the possible influence of time-specific biological processes, it is important to note that even (the onset and duration of) sensitive periods are largely influenced by experience (cf. Hensch, 2004). For example, it has been demonstrated that once a neural network is shaped by a particular environmental input, it is difficult to alter the neuronal connections by subsequent experience. These effects are independent of the age of the system (Munakata et al., 2004; Munakata and Pfaffly, 2004). At the same time, if the expected input is not yet received, the network may remain sensitive to new experience for a longer period (Hensch, 2004). Taken together, it seems that the periods of increased sensitivity to training effects are not simply guided by age, but rather by experience-related maturation (Hensch, 2004; Munakata et al., 2004; Munakata and Pfaffly, 2004).

2. Do training effects reflect long-lasting changes of brain structure or flexibility of brain function?

Besides the neural changes associated with memory of the trained material and the training itself, training-related changes in information processing are not necessarily caused by long-lasting alterations of the underlying brain structure. Performance improvements can also reflect flexibility of brain function that takes place within the limits of the current structural constraints of the brain (cf. Posner and Rothbart, 2005; Noack et al., 2009; Lövdén et al., 2010a). For instance, it has been suggested that the failure of young children to rehearse the items that are to be remembered during a working memory task often reflects a “production deficiency” (e.g., Flavell et al., 1966; Keeney et al., 1967). This indicates that children are able to apply the rehearsal strategy, but they do not always use it. Therefore, training may improve performance by encouraging children to use the strategy (e.g., Keeney et al., 1967; Ford et al., 1984), without inducing structural changes of the brain that increase working memory capacity directly.

Lövdén et al. (2010a) suggested that structural changes only take place when there is a mismatch between the environmental demands and the possibilities of the current structural system. For example, if children practice with a working memory task that requires them to hold more items in mind than they are able to (despite their use of rehearsal strategies), there is a mismatch between the demands of the training paradigm and the supply of the system (i.e., the working memory capacity). As a result, the training may increase working memory capacity by inducing plastic changes within the frontoparietal network that is involved in working memory (cf. Klingberg, 2010). The mismatch hypothesis might therefore explain why adaptive training can be more successful than non-adaptive training (Klingberg et al., 2002, 2005; Holmes et al., 2009a; Bergman Nutley et al., 2011). Noteworthy, it has been emphasized that a mismatch is a necessary, but not a sufficient condition for inducing long-term structural changes (Lövdén et al., 2010a). That is, some structural changes are not possible (e.g., working memory capacity cannot be increased infinitely). Moreover, it is important that the training is long enough for the specific structural changes to occur and that the training is not too difficult (Lövdén et al., 2010a). Finally, the degree to which plasticity is possible differs between individuals, depending on genetic factors and prior environmental influences.

3. How does training influence developmental trajectories?

It is important to consider the effect of training on the continuing developmental trajectory of the individual. First of all, training may simply "speed-up" development, such that cognitive processing/ brain structure after training is more similar to that of older children (**Figure 1**, arrow A). This is in line with the idea that development is driven by an interaction between prespecified biological maturation and experience (Stiles, 2008) and the suggestion that development and learning can be regarded as two ends of the same continuum (Galvan, 2010). Yet, training and development do not necessarily involve the exact same underlying mechanisms. It has been argued that (early) development relies to a large extent on experience-expectant neural mechanisms, while training is more influenced by experience-dependent processes (cf. Galvan, 2010). As described by Greenough et al. (1987), experience-expectant mechanisms involve neural processes that occur during particular phases of development (such as the overproduction and subsequent pruning of neurons or synaptic connections), and are driven by environmental input that is common to all members of a species. Experience-dependent mechanisms on the other hand are driven by input that is more specific to an individual and involve neural processes that are available throughout lifetime (including the formation of new synapses and changes in the efficiency of synaptic contacts). The potential difference between developmental and training-related mechanisms suggests that training could influence cognitive processing/brain structure in a way that deviates from the typical developmental trajectory (**Figure 1**, arrow B).

Neuroimaging methods might give insight in the different mechanisms that underlie typical development and training-related changes. For example, it has repeatedly been demonstrated that gray matter volume decreases during late childhood and adolescence (Sowell et al., 2001, 2003; Giedd, 2004; Gogtay et al., 2004). In contrast, adults who were learning to juggle (Draganski et al., 2004; Scholz et al., 2009), studied for exams (Draganski et al., 2006; Ceccarelli et al., 2009), or practiced mirror-reading (Ilg et al., 2008) showed *increased* gray matter volume in several

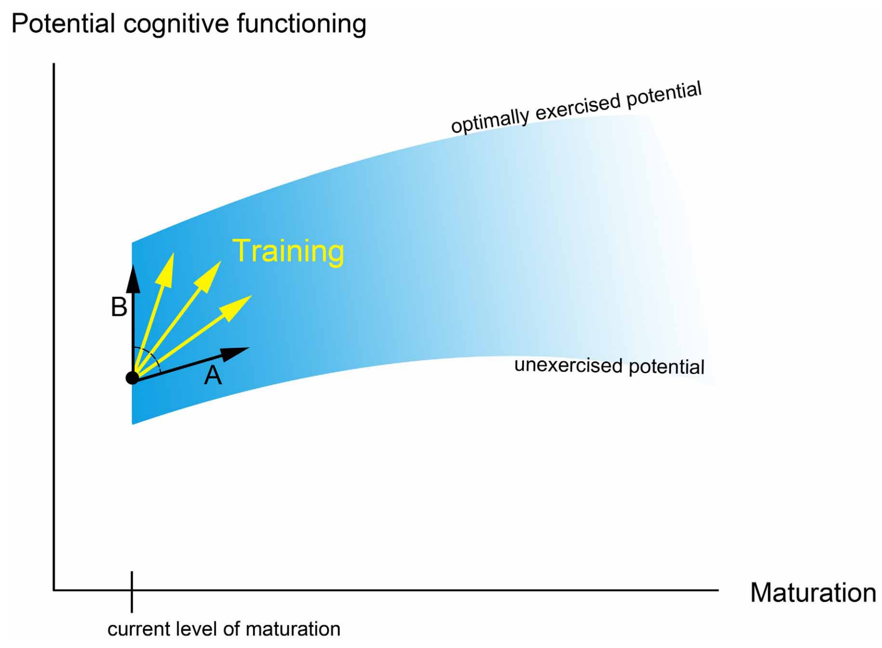

FIGURE 1 | This figure shows a simplified, metaphorical description of how training might influence developmental trajectories [based on Denney (1984); see also Hertzog et al. (2009)]. The blue curve shows the potential of cognitive functioning, which increases with age due to maturational changes and common environmental experience. In addition, optimal environmental input and training determine whether the "optimally exercised potential" (i.e., the upper limit of cognitive functioning at a certain age; Denney, 1984) can be reached. Arrow A shows how training may improve cognitive functioning by speeding-up development; arrow B shows how training might improve functioning in a way that deviates from the typical developmental trajectory.

of these areas (but see also Takeuchi et al., 2011). This suggests that on the one hand training in children may speed-up development and lead to decreased gray matter volume. On the other hand training may increase gray matter volume, like it often does in adults. Developmental training studies are needed to investigate the potential differences between typical development and training-related changes across a wide range of domains, and examine what are the long-term effects of training in terms of later developmental trajectories.

Finally, it has been argued that the "immature" brain structure actually has some important evolutionary benefits, and that speeding-up the development of cognitive control abilities in children might even have some disadvantages (cf. Bjorklund et al., 2009). For example, it has been suggested that language learning is only successful in neural networks with limited cognitive control and working memory (Newport, 1990; Elman, 1993; Ramscar and Gitcho, 2007; Thompson-Schill et al., 2009). Moreover, with advancing levels of expertise and knowledge, individuals usually develop certain routines, which might impair attentiveness and creativity (cf. Hertzog et al., 2009; Thompson-Schill et al., 2009). Yet, these findings do not necessarily mean that we should be reluctant to use training studies in childhood. It is expected that at each developmental stage there will be gains and losses (Willis and Schaie, 2009), and during childhood the gains of training will probably outweigh the losses. Nevertheless, the hypothesized disadvantages of training require further attention in the future.

NEUROIMAGING STUDIES OF COGNITIVE TRAINING

Neuroimaging methods provide a promising approach to increase our insight in the underlying mechanisms that drive training effects, and they can be used to make predictions about transfer effects (Dahlin et al., 2008). An additional advantage of neuroimaging data is that they can be analyzed along several dimensions (e.g., magnitude, location, or dynamics of activation and connectivity), which may result in increased sensitivity compared with behavioral measures (cf. Lustig et al., 2009). To describe the range of possible training outcomes irrespective of development, we start with a brief description of neuroimaging effects of training in adults, with a particular focus on the domain of working memory and cognitive control. For an extensive overview of training effects in the adult brain, we refer to prior reviews (Kelly and Garavan, 2005; Lustig et al., 2009; Buschkuehl et al., 2012).

Changes of brain activation

Depending on the cognitive and neural processes involved, cognitive training may lead to increased activation, reduced activation, and/or a change in the spatial pattern of activation (Poldrack, 2000; Jonides, 2004; Kelly and Garavan, 2005). It has been argued that simple process-based training often changes the level of activation within the functional network that was already recruited before practice (Chein and Schneider, 2005; Kelly and Garavan, 2005). The majority of cognitive training studies have demonstrated frontoparietal activation decreases in this respect, particularly if the training was very short (e.g., Garavan et al., 2000; Jansma et al., 2001; Landau et al., 2004; Tomasi et al., 2004; Sayala et al., 2006). Nevertheless, decreases have also been observed after longer training periods (Hempel et al., 2004; Schneiders et al., 2011). There are several possible explanations for these activation decreases, including reduced reliance on executive control and error monitoring, increased speed of processing, repetition priming (i.e., implicit memory for task stimuli leading to faster identification), and/or increased specificity of neuronal responses in the underlying neural network (cf. Poldrack, 2000). Yet, the magnitude and direction of training-related activation changes probably depend on specific task demands and the difficulty level of the task (Jolles et al., 2010). It has been hypothesized that cognitive training should only result in reduced activation if the task is within capacity limits (cf. Nyberg et al., 2009). This might explain why young adults showed frontoparietal activation decreases after training in working memory updating (in addition to increased activation in the striatum), while older adults–who likely had a lower working memory capacity–showed activation increases (Dahlin et al., 2008). Moreover, when task load was dynamically adapted to the ability of participants (i.e., by increasing the number of items to be held in working memory), increased frontoparietal activation has also been found in young adults (Olesen et al., 2004; but see also Schneiders et al., 2011). More specifically, the authors found training-related activation increases in middle frontal gyrus and superior and inferior parietal cortices (along with decreases in the cingulate cortex), which they attributed to an increase of working memory capacity (Olesen et al., 2004; Klingberg, 2010).

When participants learn to employ a new strategy, a change in the spatial pattern of functional activation is often observed (cf. Poldrack, 2000; Chein and Schneider, 2005; Kelly and Garavan, 2005). Furthermore, it has been suggested that the use of new strategies may lead to increased activation in frontoparietal control regions, even when these strategies lessen task demands (Bor and Owen, 2007b). For example, in a series of experiments Bor et al. (2004; 2003; Bor and Owen, 2007a) showed that when participants used chunking strategies to maintain information in working memory, frontoparietal activation increased, although task difficulty decreased. In addition, it has been demonstrated that when participants were trained in using semantic or visuospatial strategies for the encoding of word lists, they showed improved recall and increased activation in frontal and/or occipitoparietal cortex (Nyberg et al., 2003; Miotto et al., 2006). Finally, a strategy change may also induce a shift in the dynamics of activation. For example, using a short strategy training in a group of older adults, Braver et al. (2009) demonstrated a shift from probe-based to cue-based activation in prefrontal cortex regions. This shift was interpreted as a change from a reactive toward a more proactive control mode.

Changes of functional connectivity

In addition to changes in the level of activation within regions, training can also induce changes in the interaction between regions. Such interactions can be studied using functional connectivity (i.e., temporal correlations of blood oxygen level dependent (BOLD) signal fluctuations between brain regions) and effective connectivity (i.e., the influence that one region exerts over another) (for a detailed discussion of these concepts, see Friston, 1994). For example, connectivity changes have been observed during artificial grammar learning (Fletcher et al., 1999), repetition suppression (Buchel et al., 1999), visual categorization learning (DeGutis and D'Esposito, 2009), and in experts versus non-experts during a creativity task (Kowatari et al., 2009). Moreover, training-related changes of functional connectivity have been observed during resting-state (Albert et al., 2009; Lewis et al., 2009; Jolles et al., 2011), suggesting that changes of interregional interactions are not necessarily specific to task conditions. For example, Jolles et al. (2011) showed that practice with a working memory task changed functional connectivity during a rest period preceding the task. More specifically, regions of the frontoparietal task network showed increased resting-state functional connectivity after training, whereas regions of the default mode network showed reduced functional connectivity after training. Future studies should examine whether these changes were associated with repeated co-activation during the practice period or with preparatory processes regarding the upcoming task.

Changes of brain structure

It remains to be determined to which extent changes of brain activation or functional connectivity are directly related to changes of the underlying brain structure. Functional changes could be associated with a multitude of different structural changes, including changes in the number or efficacy of synapses, myelination, and changes of hormone or neurotransmitter systems. However, only a subset of structural changes can be observed using neuroimaging methods (cf. Poldrack, 2000). For example, a number of studies have demonstrated changes in gray- and/or white matter structure (Draganski et al., 2006; Ceccarelli et al., 2009; Lövdén et al., 2010b; Takeuchi et al., 2010; Garavan et al., 2000), and in the density of dopamine receptors (McNab et al., 2009). Interestingly, one study demonstrated a correspondence between regions that were activated during the trained task (i.e., mirror reading), regions that showed practice-related activation increases, and regions that showed changes of gray matter volume (Ilg et al., 2008). However, it is important to note that these results do not automatically imply causality, and further studies are necessary to specify the interaction between functional and structural changes as a result of training.

TRAINING THE DEVELOPING BRAIN

In general, practice may induce similar changes of brain function (or structure) in children as are seen in adults, including reduced activation with increasing automaticity, and a reorganization of neural activation after a strategy change. Yet, it is important to acknowledge that the child brain is not just a simplified, less efficient version of the adult brain (cf. Poldrack, 2010). As described in the section about Training effects in the context of the developing brain, training in children may speed-up developmental change, such that brain function is more similar to adult brain function after training. Yet, training could also have qualitatively different effects in children and adults.

There are only a few neuroscientific studies that examined activation changes after cognitive training in children. The first set of studies has demonstrated that training may speed-up developmental changes, such that neural activation in children is more similar to that of older children or adults. For instance, it has been suggested that children show a more "mature" pattern of frontoparietal brain activation after working memory practice (Jolles et al., 2012). Previously, it had been demonstrated that 8–12-year-old children did not show increased activation for manipulation of information in working memory above and beyond the regions they used for pure maintenance (Crone et al., 2006). However, after six weeks of practice, children showed increased activation in the frontoparietal network for manipulation relative to maintenance, arguing against the hypothesis that these regions were "inaccessible" due to immature neural circuitry (Jolles et al., 2012). A similar effect has been described for 6-year-old children who participated in training of executive attention (Rueda et al., 2005). After training, the children showed a more adult-like scalp distribution of event-related potentials (ERPs) than children of a control group. Notably, this study also pointed out that there might be limits on the effects of practice in childhood, as 4-year-olds did not show this effect (Rueda et al., 2005). These findings suggest that training of a particular brain function requires a certain stage of cognitive and/or structural brain development.

There are also studies indicating that children and adults process practiced information differently than adults. For example, after practicing for several days with algebra, children showed reduced activation in prefrontal and parietal cortex and increased activation in left putamen (Qin et al., 2004). In contrast, adults who practiced with a similar task only showed reduced prefrontal activation (Qin et al., 2003). It remains to be determined whether these results indicate increased plasticity, or whether they are related to immature processing in children (Luna, 2004). One study specifically examined the link between activation and changes of the underlying brain structure (Haier et al., 2009). In this study, adolescent girls practiced for three months with a visuospatial computer game (tetris). After practice, they showed increased cortical thickness in superior frontal and temporal areas, as well as decreased activation in frontal and parietal areas. Training-related activation changes did not overlap with changes of cortical thickness, suggesting that changes of activation are not necessarily the result of structural changes in the same location.

Finally, a number of studies have examined the malleability of brain function in children with developmental disabilities, such as attention deficit hyperactivity disorder (ADHD), developmental dyscalculia (i.e., a specific deficit in learning mathematics), and dyslexia. For instance, it has been demonstrated that cognitive training changes task performance and brain activation in children diagnosed with ADHD (Hoekzema et al., 2010). The authors emphasized that the training-related activation changes were found in syndrome-associated brain regions in frontal lobe and cerebellum, which are also target of psychostimulant medication. These findings point out the potential benefit of cognitive training as part of ADHD-treatment (cf. Hoekzema et al., 2010). Another study examined how children with and without developmental dyscalculia responded to mental number line training (Kucian et al., 2011). After training, both groups showed improved performance, as well as decreased activation in task-related areas. The decrease was stronger in children with developmental dyscalculia. This seems contradictive with the group differences before training, when children with developmental dyscalculia showed less activation compared to typically developing children. Yet, follow-up results in a subgroup of the dyscalculics indicated that there might be a normalization of brain function after a few weeks. However, it should be noted that these results were based on only seven children and require validation in future research. Neural activation changes have also been observed in children with language disorders, including reading disability, dyslexia, and specific language impairment (Simos et al., 2002; Aylward et al., 2003; Temple et al., 2003; Shaywitz et al., 2004; Stevens et al., 2008). Interestingly, Stevens et al. (2008) showed that language training did not only improve standardized measures of receptive language, it also influenced neural mechanisms related to auditory attention. That is, children with specific language impairment showed an increase in the ERP component associated with selective auditory attention after training. These findings are in line with the idea that language interventions might improve language skills in part by training domain-general systems such as attention or memory, which provides an interesting direction for future research (Stevens et al., 2008). Furthermore, future studies in children with developmental disabilities should examine the extent to which early interventions can change or even normalize developmental trajectories in later childhood or adolescence. Long-term effects are one of the most important measures to determine the effectiveness of training programs that are developed for intervention purposes.

CRITICAL CONSIDERATIONS AND FUTURE DIRECTIONS

In the present article, we suggested that training effects are better understood in the context of the developing brain, because they emerge from a dynamic interaction between learning and brain maturation (cf. Galvan, 2010). In addition, by providing a short overview of the effects of neurocognitive training studies, we illustrated how neuroimaging methods can contribute to our understanding of the underlying cognitive and neural processes that are involved during training. In this paragraph, we point out the issues that warrant further attention in future research.

NEUROIMAGING METHODS: CONFOUNDS AND CONSIDERATIONS

We have described how neuroimaging tools can be valuable in providing additive insights in the underlying cognitive and neural processes that are involved in training. In addition, neuroimaging data may be more sensitive than behavioral measures (cf. Lustig et al., 2009). However, a serious challenge is the complexity of the results. There are multiple cognitive and neural mechanisms that can drive changes in activation or brain structure, and these mechanisms might be different for children and adults. Thus, even if developmental and experience-related changes are similar, they are not necessarily caused by the same cognitive or neural processes (cf. Klingberg, 2006). Moreover, there is a number of confounding factors that further complicate the interpretation of activation changes after practice, including changes in task performance, scanner instability, or reduced anxiety (**Box 1**). Therefore, it is important to perform theory-driven experiments with well-described tasks and to control for variables that are not of interest (Poldrack, 2000; Luna et al., 2010; Crone and Ridderinkhof, 2011). In addition, human training studies might be conducted in parallel with animal studies and/or with neural network modeling to create hypotheses about the underlying anatomical, histological, and neurochemical processes that are involved during training. Prior studies have already demonstrated the value of computational modeling in describing how plasticity and learning may differ between children adults (e.g., Elman, 1993; Thomas and Karmiloff-Smith, 2002). In the future, it will be of great value to combine computational modeling with neuroimaging methods to create predictions about training-related changes in the BOLD signal (Macoveanu et al., 2006; Edin et al., 2007, 2009).

INDIVIDUAL DIFFERENCES AND ENVIRONMENTAL FACTORS

We pointed out that inter- and intraindividual differences in training outcome depend on an interaction between genetic differences and prior experience. Individual differences might be evident in the ability to learn from training, the rate of learning, and the maximum level of cognitive functioning that can be achieved (cf. Mercado, 2008; Willis and Schaie, 2009). Moreover, individual differences in training gain have been shown to moderate transfer effects (Jaeggi et al., 2011). One important focus for future research involves the characterization of individual and environmental factors that define differences in training gain, and to determine how these factors are related to differences in brain function and structural brain maturation. Studies in adults have already demonstrated that individual differences in internalized beliefs and goals can influence learning success and that these differences are related to differences in the ERP response (e.g., Mangels et al., 2006). Moreover, there are indications that individual differences in brain structure predict performance improvements (Golestani et al., 2002; Erickson et al., 2010). In children, these mechanisms might even be more complex. Shaw et al. (2006) demonstrated that there are differences between children in the trajectory of cortical development, with more intelligent children showing a prolonged phase of structural brain maturation compared with less intelligent children. These findings indicate that individual differences in training gain could be influenced by the "maturity" of the underlying brain structure, regardless of the child's age.

Another factor that should be considered when examining training gain is the input from the environment that an individual receives (both in terms of schooling and positive or negative reinforcement). For example, it has been argued that children who receive optimal education and stimulation have a large "actualized genetic potential" (Bronfenbrenner and Ceci, 1994), which suggests that extra training will have less additional value. This may explain why cognitive intervention programs are particularly effective in children from a low socioeconomic background (Brooks-Gunn et al., 1992; Mezzacappa and Buckner, 2010; Mackey et al., 2011). In a similar vein, it has been argued that functions that are frequently practiced in every-day situations might be more difficult to train than less practiced functions (Denney, 1984). Moreover, according to the time displacement hypothesis (e.g., Bavelier et al., 2010), training may even lead to negative effects if the activities it displaces are more beneficial than the training itself.

SUMMARY AND CONCLUSION

We aimed to show in this review that training studies provide important tools in studying the possibilities and limitations of cognitive functioning over the course of childhood. We described that training effects in the developing brain are driven by a complex interaction between learning, brain development, genetic differences and prior experience. Depending on the type of training and the level of maturation of the individual, training may speed-up development; improve the individual's actualized genetic potential; or both. The immature brain structure can set limits on how much can be achieved with training, but in some cases these same limitations could be an advantage. We argued that neuroimaging methods have a great potential to improve our understanding of the interaction between learning and brain development. Rather than examining *whether* training studies are effective, neuroimaging studies may provide insight into *how* training interventions are effective. Yet, there is a still number of challenges and confounds to overcome.

Although we must be careful when translating scientific research to practical applications (Bruer, 1997; Goswami, 2006), neurocognitive training studies have potential for application in practice. Eventually, they might aid in designing education programs and interventions for normally developing children or children with developmental disabilities (Posner and Rothbart, 2005; Goswami, 2006; Carew and Magsamen, 2010). For example, to optimize education programs, it is valuable to know more about how children at different ages learn a particular skill, how the underlying neural circuitry supports different kinds of learning, and whether the learning-related changes reflect flexibility in brain function or more permanent changes of the underlying brain structure (Posner and Rothbart, 2005; Goswami, 2006; Carew and Magsamen, 2010). In addition, knowledge about children's abilities to learn might yield insights about specific learning problems, as seen for example in children with dyslexia, or ADHD. When the underlying cause of children's learning difficulties is better understood, it might be possible to target intervention to remediate these difficulties (Goswami, 2006).

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REFERENCES

Albert, N. B., Robertson, E. M., and Miall, R. C. (2009). The resting human brain and motor learning. *Curr. Biol.* 19, 1023–1027.

Aylward, E. H., Richards, T. L., Berninger, V. W., Nagy, W. E., Field, K. M., Grimme, A. C., Richards, A. L., Thomson, J. B., and Cramer, S. C. (2003). Instructional treatment associated with changes in brain activation in children with dyslexia. *Neurology* 61, 212–219.

Baltes, P. B., and Kliegl, R. (1992). Further testing of limits of cognitive plasticity: negative age differences in a mnemonic skill are robust. *Dev. Psychol.* 28, 121–125.

Bangirana, P., Giordani, B., John, C. C., Page, C., Opoka, R. O., and Boivin, M. J. (2009). Immediate neuropsychological and behavioral benefits of computerized cognitive rehabilitation in Ugandan pediatric cerebral malaria survivors. *J. Dev. Behav. Pediatr.* 30, 310–318.

Bavelier, D., Green, C. S., and Dye, M. W. (2010). Children, wired: for better and for worse. *Neuron* 67, 692–701.

Beck, S. J., Hanson, C. A., Puffenberger, S. S., Benninger, K. L., and Benninger, W. B. (2010). A controlled trial of working memory training for children and adolescents with ADHD. *J. Clin. Child Adolesc. Psychol.* 39, 825–836.

Bergman Nutley, S., Soderqvist, S., Bryde, S., Thorell, L. B., Humphreys, K., and Klingberg, T. (2011). Gains in fluid intelligence after training non-verbal reasoning in 4-year-old children: a controlled, randomized study. *Dev. Sci.* 14, 591–601.

Bjorklund, D. F., Periss, V., and Causey, K. (2009). The benefits of youth. *Eur. J. Dev. Psychol.* 6, 120–137.

Bor, D., Cumming, N., Scott, C. E. L., and Owen, A. M. (2004). Prefrontal cortical involvement in verbal encoding strategies. *Eur. J. Neurosci.* 19, 3365–3370.

Bor, D., Duncan, J., Wiseman, R. J., and Owen, A. M. (2003). Encoding strategies dissociate prefrontal activity from working memory demand. *Neuron* 37, 361–367.

Bor, D., and Owen, A. M. (2007a). A common prefrontal-parietal network for mnemonic and mathematical recoding strategies within working memory. *Cereb. Cortex.* 17, 778–786.

Bor, D., and Owen, A. M. (2007b). Cognitive training: neural correlates of expert skills. *Curr. Biol.* 17, R95–R97.

Bors, D. A., and Vigneau, F. (2001). The effect of practice on Raven's advanced progressive matrices. *Learn. Individ. Differ.* 13, 291–312.

Braver, T. S., Paxton, J. L., Locke, H. S., and Barch, D. M. (2009). Flexible neural mechanisms of cognitive control within human prefrontal cortex. *Proc. Natl. Acad. Sci. U.S.A.* 106, 7351–7356.

Brefczynski-Lewis, J. A., Lutz, A., Schaefer, H. S., Levinson, D. B., and Davidson, R. J. (2007). Neural correlates of attentional expertise in long-term meditation practitioners. *Proc. Natl. Acad. Sci. U.S.A.* 104, 11483–11488.

Bronfenbrenner, U., and Ceci, S. J. (1994). Nature-nurture reconceptualized in developmental perspective: a bioecological model. *Psychol. Rev.* 101, 568–586.

Brooks-Gunn, J., Gross, R. T., Kraemer, H. C., Spiker, D., and Shapiro, S. (1992). Enhancing the cognitive outcomes of low birth weight, premature infants: for whom is the intervention most effective? *Pediatrics* 89, 1209.

Bruer, J. T. (1997). Education and the brain: a bridge too far. *Educ. Res.* 26, 4–16.

Bryck, R. L., and Fisher, P. A. (2012). Training the brain: practical applications of neural plasticity from the intersection of cognitive neuroscience, developmental psychology, and prevention science. *Am. Psychol.* 67, 87–100.

Buchel, C., Coull, J. T., and Friston, K. J. (1999). The predictive value of changes in effective connectivity for human learning. *Science* 283, 1538–1541.

Buckner, R. L., Ndrews-Hanna, J. R., and Schacter, D. L. (2008). The brain's default network: anatomy, function, and relevance to disease. *Ann. N.Y. Acad. Sci.* 1124, 1–38.

Buschkuehl, M., and Jaeggi, S. M. (2010). Improving intelligence: a literature review. *Swiss Med. Wkly.* 140, 266–272.

Buschkuehl, M., Jaeggi, S. M., and Jonides, J. (2012). Neuronal effects following working memory training. *Dev. Cogn. Neurosci.* 2, S167–S179.

Carew, T. J., and Magsamen, S. H. (2010). Neuroscience and education: an ideal partnership for producing evidence-based solutions to Guide 21(st) Century Learning. *Neuron* 67, 685–688.

Case, R., Kurland, D. M., and Goldberg, J. (1982). Operational efficiency and the growth of short-term memory span. *J. Exp. Child Psychol.* 33, 386–404.

Casey, B. J., Tottenham, N., Liston, C., and Durston, S. (2005). Imaging the developing brain: what have we learned about cognitive development? *Trends Cogn. Sci.* 9, 104–110.

Ceccarelli, A., Rocca, M. A., Pagani, E., Falini, A., Comi, G., and Filippi, M. (2009). Cognitive learning is associated with gray matter changes in healthy human individuals: a tensor-based morphometry study. *Neuroimage* 48, 585–589.

Changeux, J. P., and Danchin, A. (1976). Selective stabilisation of developing synapses as a mechanism for the specification of neuronal networks. *Nature* 264, 705–712.

Chechik, G., Meilijson, I., and Ruppin, E. (1998). Synaptic pruning in development: a computational account. *Neural Comput.* 10, 1759–1777.

Chein, J. M., and Schneider, W. (2005). Neuroimaging studies of practice-related change: fMRI and meta-analytic evidence of a domain-general control network for learning. *Brain Res. Cogn. Brain Res.* 25, 607–623.

Chenault, B., Thomson, J., Abbott, R. D., and Berninger, V. W. (2006). Effects of prior attention training on child dyslexics' response to composition instruction. *Dev. Neuropsychol.* 29, 243–260.

Church, J. A., Petersen, S. E., and Schlaggar, B. L. (2010). The "Task B problem" and other considerations in developmental functional neuroimaging. *Hum. Brain Mapp.* 31, 852–862.

Conners, F. A., Rosenquist, C. J., Arnett, L., Moore, M. S., and Hume, L. E. (2008). Improving memory span in children with Down syndrome. *J. Intellect. Disabil. Res.* 52, 244–255.

Crone, E. A., and Ridderinkhof, R. K. (2011). The developing brain: from theory to neuroimaging and back. *Dev. Cogn. Neurosci.* 1, 101–109.

Crone, E. A., Wendelken, C., Donohue, S., van Leijenhorst, L., and Bunge, S. A. (2006). Neurocognitive development of the ability to manipulate information in working memory. *Proc. Natl. Acad. Sci. U.S.A.* 103, 9315–9320.

Dahlin, K. I. E. (2011). Effects of working memory training on reading in children with special needs. *Reading Writ.* 24, 479–491.

Dahlin, E., Neely, A. S., Larsson, A., Backman, L., and Nyberg, L. (2008). Transfer of learning after updating training mediated by the striatum. *Science* 320, 1510–1512.

DeGutis, J., and D'Esposito, M. (2009). Network changes in the transition from initial learning to well-practiced visual categorization. *Front. Hum. Neurosci.* 3:44. doi: 10.3389/neuro.09.044.2009

Denney, N. W. (1984). A model of cognitive development across the life span. *Dev. Rev.* 4, 171–191.

Diamond, A., and Lee, K. (2011). Interventions shown to aid executive function development in children 4 to 12 years old. *Science* 333, 959–964.

Draganski, B., Gaser, C., Busch, V., Schuierer, G., Bogdahn, U., and May, A. (2004). Neuroplasticity: changes in grey matter induced by training. *Nature* 427, 311–312.

Draganski, B., Gaser, C., Kempermann, G., Kuhn, H. G., Winkler, J., Buchel, C., and May, A. (2006). Temporal and spatial dynamics of brain structure changes during extensive learning. *J. Neurosci.* 26, 6314–6317.

Duncan, J., and Owen, A. M. (2000). Common regions of the human frontal lobe recruited by diverse cognitive demands. *Trends Neurosci.* 23, 475–483.

Edin, F., Klingberg, T., Johansson, P., McNab, F., Tegner, J., and Compte, A. (2009). Mechanism for top-down control of working memory capacity. *Proc. Natl. Acad. Sci. U.S.A.* 106, 6802–6807.

Edin, F., Macoveanu, J., Olesen, P., Tegner, J., and Klingberg, T. (2007). Stronger synaptic connectivity as a mechanism behind development of working memory-related brain activity during childhood. *J. Cogn. Neurosci.* 19, 750–760.

Elbert, T., Pantev, C., Wienbruch, C., Rockstroh, B., and Taub, E. (1995). Increased cortical representation of the fingers of the left hand in string players. *Science* 270, 305–307.

Elman, J. L. (1993). Learning and development in neural networks: the importance of starting small. *Cognition* 48, 71–99.

Erickson, K. I., Boot, W. R., Basak, C., Neider, M. B., Prakash, R. S., Voss, M. W., Graybiel, A. M., Simons, D. J., Fabiani, M., and Gratton, G. (2010). Striatal volume predicts level of video game skill acquisition. *Cereb. Cortex* 20, 2522.

Fields, R. D. (2008). White matter in learning, cognition and psychiatric disorders. *Trends Neurosci.* 31, 361–370.

Flavell, J. H., Beach, D. R., and Chinsky, J. M. (1966). Spontaneous verbal rehearsal in a memory task as a function of age. *Child Dev.* 37, 283–299.

Fletcher, P., Buchel, C., Josephs, O., Friston, K., and Dolan, R. (1999). Learning-related neuronal responses in prefrontal cortex studied with functional neuroimaging. *Cereb. Cortex* 9, 168–178.

Ford, C. E., Pelham, W. E., and Ross, A. O. (1984). Selective attention and rehearsal in the auditory short-term memory task performance of poor and normal readers. *J. abnorm. child psychol.* 12, 127–141.

Friston, K. (1994). Functional and effective connectivity in neuroimaging: a synthesis. *Hum. Brain Mapp.* 2, 56–78.

Galvan, A. (2010). Neural plasticity of development and learning. *Hum. Brain Mapp.* 31, 879–890.

Garavan, H., Kelley, D., Rosen, A., Rao, S. M., and Stein, E. A. (2000). Practice-related functional activation changes in a working memory task. *Microsc. Res. Tech.* 51, 54–63.

Gaser, C., and Schlaug, G. (2003). Brain structures differ between musicians and non-musicians. *J. Neurosci.* 23, 9240–9245.

Ghatala, E. S., Levin, J. R., Pressley, M., and Lodico, M. G. (1985). Training cognitive strategy-monitoring in children. *Am. Educ. Res. J.* 22, 199.

Giedd, J. N. (2004). Structural magnetic resonance imaging of the adolescent brain. *Ann. N.Y. Acad. Sci.* 1021, 77–85.

Giedd, J. N., and Rapoport, J. L. (2010). Structural MRI of pediatric brain development: what have we learned and where are we going? *Neuron* 67, 728–734.

Gogtay, N., Giedd, J. N., Lusk, L., Hayashi, K. M., Greenstein, D., Vaituzis, A. C., Nugent, T. F., Herman, D. H., Clasen, L. S., Toga, A. W., Rapoport, J. L., and Thompson, P. M. (2004). Dynamic mapping of human cortical development during childhood through early adulthood. *Proc. Natl. Acad. Sci. U.S.A.* 101, 8174–8179.

Goldman-Rakic, P. S. (1987). Development of cortical circuitry and cognitive function. *Child Dev.* 58, 601–622.

Golestani, N., Paus, T., and Zatorre, R. J. (2002). Anatomical correlates of learning novel speech sounds. *Neuron* 35, 997–1010.

Goodyear, B. G., and Douglas, E. A. (2009). Decreasing task-related brain activity over repeated functional MRI scans and sessions with no change in performance: implications for serial investigations. *Exp. Brain Res.* 192, 231–239.

Goswami, U. (2006). Neuroscience and education: from research to practice? *Nat. Rev. Neurosci.* 7, 406–411.

Green, C. S., and Bavelier, D. (2008). Exercising your brain: a review of human brain plasticity and training-induced learning. *Psychol. Aging* 23, 692–701.

Greenough, W. T., Black, J. E., and Wallace, C. S. (1987). Experience and brain development. *Child Dev.* 58, 539–559.

Haier, R. J., Karama, S., Leyba, L., and Jung, R. E. (2009). MRI assessment of cortical thickness and functional activity changes in adolescent girls following three months of practice on a visual-spatial task. *BMC Res. Notes* 2, 174.

Heathcote, A., Brown, S., and Mewhort, D. J. (2000). The power law repealed: the case for an exponential law of practice. *Psychon. Bull. Rev.* 7, 185–207.

Hempel, A., Giesel, F. L., Garcia Caraballo, N. M., Amann, M., Meyer, H., Wustenberg, T., Essig, M., and Schroder, J. (2004). Plasticity of cortical activation related to working memory during training. *Am. J. Psychiatry* 161, 745–747.

Hensch, T. K. (2004). Critical period regulation. *Annu. Rev. Neurosci.* 27, 549–579.

Hertzog, C., Kramer, A. F., Wilson, R. S., and Lindenberger, U. (2009). Enrichment effects on adult cognitive development. Can the functional capacity of older adults be preserved and enhanced? *Psychol. Sci. Public Interest* 9, 1–65.

Hoekzema, E., Carmona, S., Tremols, V., Gispert, J. D., Guitart, M., Fauquet, J., Rovira, M., Bielsa, A., Soliva, J. C., Tomas, X., Bulbena, A., Ramos-Quiroga, A., Casas, M., Tobena, A., and Vilarroya, O. (2010). Enhanced neural activity in frontal and cerebellar circuits after cognitive training in children with attention-deficit/hyperactivity disorder. *Hum. Brain Mapp.* 31, 1942–1950.

Holmes, J., Gathercole, S. E., and Dunning, D. L. (2009a). Adaptive training leads to sustained enhancement of poor working memory in children. *Dev. Sci.* 12, F9–F15.

Holmes, J., Gathercole, S. E., Dunning, D. L., Hilton, K. A., and Elliott, J. G. (2009b). Working memory deficits can be overcome: impacts of training and medication on working memory in children with ADHD. *Appl. Cogn. Psychol.* 24, 827–836.

Huizinga, M., Dolan, C. V., and Van der Molen, M. W. (2006). Age-related change in executive function: developmental trends and a latent variable analysis. *Neuropsychologia* 44, 2017–2036.

Huttenlocher, P. R. (2002). *Neural Plasticity: The Effects of Environment on the Development of the Cerebral Cortex (Perspectives in Cognitive Neuroscience).* Cambridge, MA: Harvard University Press.

Huttenlocher, P. R. (2003). Basic neuroscience research has important implications for child development. *Nat. Neurosci.* 6, 541–541.

Ilg, R., Wohlschlager, A. M., Gaser, C., Liebau, Y., Dauner, R., Woller, A., Zimmer, C., Zihl, J., and Muhlau, M. (2008). Gray matter increase induced by practice correlates with task-specific activation: a combined functional and morphometric magnetic resonance imaging study. *J. Neurosci.* 28, 4210–4215.

Jaeggi, S. M., Buschkuehl, M., Jonides, J., and Shah, P. (2011). Short- and long-term benefits of cognitive training. *Proc. Natl. Acad. Sci. U.S.A.* 108, 10081–10086.

Jansma, J. M., Ramsey, N. F., Slagter, H. A., and Kahn, R. S. (2001). Functional anatomical correlates of controlled and automatic processing. *J. Cogn. Neurosci.* 13, 730–743.

Johnson, M. H. (2001). Functional brain development in humans. *Nat. Rev. Neurosci.* 2, 475–483.

Johnson, M. H. (2011). Interactive specialization: a domain-general framework for human functional brain development? *Dev. Cogn. Neurosci.* 1, 7–21.

Johnstone, S. J., Roodenrys, S., Phillips, E., Watt, A. J., and Mantz, S. (2010). A pilot study of combined working memory and inhibition training for children with AD/HD. *Atten. Defic. Hyperact. Disord.* 2, 31–42.

Jolles, D. D., Grol, M. J., van Buchem, M. A., Rombouts, S. A., and Crone, E. A. (2010). Practice effects in the brain: changes in cerebral activation after working memory practice depend on task demands. *Neuroimage* 52, 658–668.

Jolles, D. D., van Buchem, M. A., Crone, E. A., and Rombouts, S. A. (2011). Functional brain connectivity at rest changes after working memory training. *Hum. Brain Mapp.* doi: 10.1002/hbm.21444. [Epub ahead of print]

Jolles, D. D., van Buchem, M. A., Rombouts, S. A. R. B., and Crone, E. A. (2012). Practice effects in the developing brain: a pilot study. *Dev. Cogn. Neurosci.* 2S, S180–S191.

Jonides, J. (2004). How does practice makes perfect? *Nat. Neurosci.* 7, 10–11.

Karbach, J., and Kray, J. (2009). How useful is executive control training? Age differences in near and far transfer of task-switching training. *Dev. Sci.* 12, 978–990.

Karmiloff-Smith, A. (2009). Nativism versus neuroconstructivism: rethinking the study of developmental disorders. *Dev. Psychol.* 45, 56–63.

Keeney, T. J., Cannizzo, S. R., and Flavell, J. H. (1967). Spontaneous and induced verbal rehearsal in a recall task. *Child Dev.* 38, 953–966.

Kelly, A. M., and Garavan, H. (2005). Human functional neuroimaging of brain changes associated with practice. *Cereb. Cortex* 15, 1089–1102.

Klingberg, T. (2006). Development of a superior frontal-intraparietal network for visuo-spatial working memory. *Neuropsychologia* 44, 2171–2177.

Klingberg, T. (2010). Training and plasticity of working memory. *Trends Cogn. Sci.* 14, 317–324.

Klingberg, T., Fernell, E., Olesen, P. J., Johnson, M., Gustafsson, P., Dahlstrom, K., Gillberg, C. G., Forssberg, H., and Westerberg, H. (2005). Computerized training of working memory in children with ADHD–a randomized, controlled trial. *J. Am. Acad. Child Adolesc. Psychiatry* 44, 177–186.

Klingberg, T., Forssberg, H., and Westerberg, H. (2002). Training of working memory in children with ADHD. *J. Clin. Exp. Neuropsychol.* 24, 781–791.

Kolb, B., Teskey, G. C., and Gibb, R. (2010). Factors influencing cerebral plasticity in the normal and injured brain. *Front. Hum. Neurosci.* 4:204. doi: 10.3389/fnhum.2010.00204

Kowatari, Y., Lee, S. H., Yamamura, H., Nagamori, Y., Levy, P., Yamane, S., and Yamamoto, M. (2009). Neural networks involved in artistic creativity. *Hum. Brain Mapp.* 30, 1678–1690.

Kramarski, B., and Mevarech, Z. R. (2003). Enhancing mathematical reasoning in the classroom: the effects of cooperative learning and metacognitive training. *Am. Educ. Res. J.* 40, 281.

Kucian, K., Grond, U., Rotzer, S., Henzi, B., Schonmann, C., Plangger, F., Galli, M., Martin, E., and von Aster, M. (2011). Mental number line training in children with developmental dyscalculia. *Neuroimage* 57, 782–795.

Landau, S. M., Schumacher, E. H., Garavan, H., Druzgal, T. J., and D'esposito, M. (2004). A functional MRI study of the influence of practice on component processes of working memory. *Neuroimage* 22, 211–221.

Lewis, C. M., Baldassarre, A., Committeri, G., Romani, G. L., and Corbetta, M. (2009). Learning sculpts the spontaneous activity of the resting human brain. *Proc. Natl. Acad. Sci. U.S.A.* 106, 17558–17563.

Loosli, S. V., Buschkuehl, M., Perrig, W. J., and Jaeggi, S. M. (2011). Working memory training improves reading processes in typically developing children. *Child Neuropsychol.* 1–17.

Lövdén, M., Backman, L., Lindenberger, U., Schaefer, S., and Schmiedek, F. (2010a). A theoretical framework for the study of adult cognitive plasticity. *Psychol. Bull.* 136, 659–676.

Lövdén, M., Bodammer, N. C., Kuhn, S., Kaufmann, J., Schutze, H., Tempelmann, C., Heinze, H. J., Duzel, E., Schmiedek, F., and Lindenberger, U. (2010b). Experience-dependent plasticity of white-matter microstructure extends into old age. *Neuropsychologia* 48, 3878–3883.

Luna, B. (2004). Algebra and the adolescent brain. *Trends Cogn. Sci.* 8, 437–439.

Luna, B., Velanova, K., and Geier, C. F. (2010). Methodological approaches in developmental neuroimaging studies. *Hum. Brain Mapp.* 31, 863–871.

Lustig, C., Shah, P., Seidler, R., and Reuter-Lorenz, P. A. (2009). Aging, training, and the brain: a review and future directions. *Neuropsychol. Rev.* 19, 504–522.

Lutz, A., Brefczynski-Lewis, J., Johnstone, T., and Davidson, R. J. (2008). Regulation of the neural circuitry of emotion by compassion meditation: effects of meditative expertise. *PLoS One* 3:e1897. doi: 10.1371/journal.pone.0001897

Mackey, A. P., Hill, S. S., Stone, S. I., and Bunge, S. A. (2011). Dissociable effects of reasoning and speed training in children. *Dev. Sci.* 14, 582–590.

Macoveanu, J., Klingberg, T., and Tegner, J. (2006). A biophysical model of multiple-item working memory: a computational and neuroimaging study. *Neuroscience* 141, 1611–1618.

Maguire, E. A., Gadian, D. G., Johnsrude, I. S., Good, C. D., Ashburner, J., Frackowiak, R. S., and Frith, C. D. (2000). Navigation-related structural change in the hippocampi of taxi drivers. *Proc. Natl. Acad. Sci. U.S.A.* 97, 4398–4403.

Maguire, E. A., Woollett, K., and Spiers, H. J. (2006). London taxi drivers and bus drivers: a structural MRI and neuropsychological analysis. *Hippocampus* 16, 1091–1101.

Mangels, J. A., Butterfield, B., Lamb, J., Good, C., and Dweck, C. S. (2006). Why do beliefs about intelligence influence learning success? A social cognitive neuroscience model. *Soc. Cogn. Affect. Neurosci.* 1, 75–86.

McNab, F., Varrone, A., Farde, L., Jucaite, A., Bystritsky, P., Forssberg, H., and Klingberg, T. (2009). Changes in cortical dopamine D1 receptor binding associated with cognitive training. *Science* 323, 800–802.

Mercado, E. (2008). Neural and cognitive plasticity: from maps to minds. *Psychol. Bull.* 134, 109.

Mezzacappa, E., and Buckner, J. C. (2010). Working memory training for children with attention problems or hyperactivity: a school-based pilot study. *Sch. Ment. Health* 2, 202–208.

Miotto, E. C., Savage, C. R., Evans, J. J., Wilson, B. A., Martins, M. G., Iaki, S., and Amaro, E. Jr. (2006). Bilateral activation of the prefrontal cortex after strategic semantic cognitive training. *Hum. Brain Mapp.* 27, 288–295.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., and Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "Frontal Lobe" tasks: a latent variable analysis. *Cogn. Psychol.* 41, 49–100.

Morrison, A. B., and Chein, J. M. (2010). Does working memory training work? The promise and challenges of enhancing cognition by training working memory. *Psychon. Bull. Rev.* 18, 46–60.

Munakata, Y., Casey, B. J., and Diamond, A. (2004). Developmental cognitive neuroscience: progress and potential. *Trends Cogn. Sci.* 8, 122–128.

Munakata, Y., and Pfaffly, J. (2004). Hebbian learning and development. *Dev. Sci.* 7, 141–148.

Newport, E. L. (1990). Maturational constraints on language learning. *Cogn. Sci.* 14, 11–28.

Noack, H., Lövdén, M., Schmiedek, F., and Lindenberger, U. (2009). Cognitive plasticity in adulthood and old age: gauging the generality of cognitive intervention effects. *Restor. Neurol. Neurosci.* 27, 435–453.

Nyberg, L., Dahlin, E., Stigsdotter, N. A., and Backman, L. (2009). Neural correlates of variable working memory load across adult age and skill: dissociative patterns within the fronto-parietal network. *Scand. J. Psychol.* 50, 41–46.

Nyberg, L., Sandblom, J., Jones, S., Neely, A. S., Petersson, K. M., Ingvar, M., and Backman, L. (2003). Neural correlates of training-related memory improvement in adulthood and aging. *Proc. Natl. Acad. Sci. U.S.A.* 100, 13728–13733.

Olesen, P. J., Westerberg, H., and Klingberg, T. (2004). Increased prefrontal and parietal activity after training of working memory. *Nat. Neurosci.* 7, 75–79.

Owen, A. M., Mcmillan, K. M., Laird, A. R., and Bullmore, E. (2005). N-back working memory paradigm: a meta-analysis of normative functional neuroimaging studies. *Hum. Brain. Mapp.* 25, 46–59.

Paus, T. (2010). Growth of white matter in the adolescent brain: myelin or axon? *Brain Cogn.* 72, 26–35.

Poldrack, R. A. (2000). Imaging brain plasticity: conceptual and methodological issues–a theoretical review. *Neuroimage* 12, 1–13.

Poldrack, R. A. (2010). Interpreting developmental changes in neuroimaging signals. *Hum. Brain Mapp.* 31, 872–878.

Posner, M. I., and Rothbart, M. K. (2005). Influencing brain networks: implications for education. *Trends Cogn. Sci.* 9, 99–103.

Qin, Y., Carter, C. S., Silk, E. M., Stenger, V. A., Fissell, K., Goode, A., and Anderson, J. R. (2004). The change of the brain activation patterns as children learn algebra equation solving. *Proc. Natl. Acad. Sci. U.S.A.* 101, 5686–5691.

Qin, Y., Sohn, M. H., Anderson, J. R., Stenger, V. A., Fissell, K., Goode, A., and Carter, C. S. (2003). Predicting the practice effects on the blood oxygenation level-dependent (BOLD) function of fMRI in a symbolic manipulation task. *Proc. Natl. Acad. Sci. U.S.A.* 100, 4951–4956.

Rabiner, D. L., Murray, D. W., Skinner, A. T., and Malone, P. S. (2010). A randomized trial of two promising computer-based interventions for students with attention difficulties. *J. Abnorm. Child Psychol.* 38, 131–142.

Raichle, M. E., Macleod, A. M., Snyder, A. Z., Powers, W. J., Gusnard, D. A., and Shulman, G. L. (2001). A default mode of brain function. *Proc. Natl. Acad. Sci. U.S.A.* 98, 676–682.

Ramscar, M., and Gitcho, N. (2007). Developmental change and the nature of learning in childhood. *Trends Cogn. Sci.* 11, 274–279.

Rueda, M. R., Rothbart, M. K., Mccandliss, B. D., Saccomanno, L., and Posner, M. I. (2005). Training, maturation, and genetic influences on the development of executive attention. *Proc. Natl. Acad. Sci. U.S.A.* 102, 14931–14936.

Sayala, S., Sala, J. B., and Courtney, S. M. (2006). Increased neural efficiency with repeated performance of a working memory task is information-type dependent. *Cereb. Cortex* 16, 609–617.

Schmiedek, F., Lövdén, M., and Lindenberger, U. (2010). Hundred days of cognitive training enhance broad cognitive abilities in adulthood: findings from the COGITO study. *Front. Aging Neurosci.* 2:27. doi: 10.3389/fnagi.2010.00027

Schneiders, J. A., Opitz, B., Krick, C. M., and Mecklinger, A. (2011). Separating intra-modal and across-modal training effects in visual working memory: an fMRI investigation. *Cereb. Cortex* 21, 2555–2564.

Scholz, J., Klein, M. C., Behrens, T. E., and Johansen-Berg, H. (2009). Training induces changes in white-matter architecture. *Nat. Neurosci.* 12, 1370–1371.

Shalev, L., Tsal, Y., and Mevorach, C. (2007). Computerized progressive attentional training (CPAT) program: effective direct intervention for children with ADHD. *Child Neuropsychol.* 13, 382–388.

Shaw, P., Greenstein, D., Lerch, J., Clasen, L., Lenroot, R., Gogtay, N., Evans, A., Rapoport, J., and Giedd, J. (2006). Intellectual ability and cortical development in children and adolescents. *Nature* 440, 676–679.

Shaywitz, B. A., Shaywitz, S. E., Blachman, B. A., Pugh, K. R., Fulbright, R. K., Skudlarski, P., Mencl, W. E., Constable, R. T., Holahan, J. M., Marchione, K. E., Fletcher, J. M., Lyon, G. R., and Gore, J. C. (2004). Development of left occipitotemporal systems for skilled reading in children after a phonologically- based intervention. *Biol. Psychiatry* 55, 926–933.

Simos, P. G., Fletcher, J. M., Bergman, E., Breier, J. I., Foorman, B. R., Castillo, E. M., Davis, R. N., Fitzgerald, M., and Papanicolaou, A. C. (2002). Dyslexia-specific brain activation profile becomes normal following successful remedial training. *Neurology* 58, 1203–1213.

Sowell, E. R., Peterson, B. S., Thompson, P. M., Welcome, S. E., Henkenius, A. L., and Toga, A. W. (2003). Mapping cortical change across the human life span. *Nat. Neurosci.* 6, 309–315.

Sowell, E. R., Thompson, P. M., Tessner, K. D., and Toga, A. W. (2001). Mapping continued brain growth and gray matter density reduction in dorsal frontal cortex: inverse relationships during postadolescent brain maturation. *J. Neurosci.* 21, 8819–8829.

St. Clair-Thompson, H., Stevens, R., Hunt, A., and Bolder, E. (2010). Improving children's working memory and classroom performance. *Educ. Psychol.* 30, 203–219.

Stevens, C., Fanning, J., Coch, D., Sanders, L., and Neville, H. (2008). Neural mechanisms of selective auditory attention are enhanced by computerized training: electrophysiological evidence from language-impaired and typically developing children. *Brain Res.* 1205, 55–69.

Stiles, J. (2008). *The Fundamentals of Brain Development; Integrating Nature and Nurture.* Cambridge, MA: Harvard University Press.

Swanson, H. L., Kehler, P., and Jerman, O. (2010). Working memory, strategy knowledge, and strategy instruction in children with reading disabilities. *J. learn. Disabil.* 43, 24.

Takeuchi, H., Sekiguchi, A., Taki, Y., Yokoyama, S., Yomogida, Y., Komuro, N., Yamanouchi, T., Suzuki, S., and Kawashima, R. (2010). Training of working memory impacts structural connectivity. *J. Neurosci.* 30, 3297–3303.

Takeuchi, H., Taki, Y., Sassa, Y., Hashizume, H., Sekiguchi, A., Fukushima, A., and Kawashima, R. (2011). Working memory training using mental calculation impacts regional gray matter of the frontal and parietal regions. *PLoS One* 6:e23175. doi: 10.1371/journal.pone.0023175

Temple, E., Deutsch, G. K., Poldrack, R. A., Miller, S. L., Tallal, P., Merzenich, M. M., and Gabrieli, J. D. (2003). Neural deficits in children with dyslexia ameliorated by behavioral remediation: evidence from functional MRI. *Proc. Natl. Acad. Sci. U.S.A.* 100, 2860–2865.

Thomas, M., and Karmiloff-Smith, A. (2002). Are developmental disorders like cases of adult brain damage? Implications from connectionist modelling. *Behav. Brain Sci.* 25, 727–750; discussion 750–787.

Tomasi, D., Ernst, T., Caparelli, E. C., and Chang, L. (2004). Practice-induced changes of brain function during visual attention: a parametric fMRI study at 4 Tesla. *Neuroimage* 23, 1414–1421.

Thompson-Schill, S. L., Ramscar, M., and Chrysikou, E. G. (2009). Cognition without control: when a little frontal lobe goes a long way. *Curr. Dir. Psychol. Sci.* 18, 259–263.

Thorell, L. B., Lindqvist, S., Bergman Nutley, S., Bohlin, G., and Klingberg, T. (2009). Training and transfer effects of executive functions in preschool children. *Dev. Sci.* 12, 106–113.

Uylings, H. B. M. (2006). Development of the human cortex and the concept of "critical" or "sensitive" periods. *Lang. Learn.* 56, 59–90.

Van der Molen, M. J., van Luit, J. E., Van der Molen, M. W., Klugkist, I., and Jongmans, M. J. (2010). Effectiveness of a computerised working memory training in adolescents with mild to borderline intellectual disabilities. *J. Intellect. Disabil. Res.* 54, 433–447.

van't Hooft, I., Andersson, K., Bergman, B., Sejersen, T., von Wendt, L., and Bartfai, A. (2005). Beneficial effect from a cognitive training programme on children with acquired brain injuries demonstrated in a controlled study. *Brain Inj.* 19, 511–518.

van't Hooft, I., Andersson, K., Sejersen, T., Bartfai, A., and von Wendt, L. (2003). Attention and memory training in children with acquired brain injuries. *Acta Paediatr.* 92, 935–940.

Wager, T. D., and Smith, E. E. (2003). Neuroimaging studies of working memory: a meta-analysis. *Cogn. Affect. Behav. Neurosci.* 3, 255–274.

Willis, S. L., and Schaie, K. W. (2009). Cognitive training and plasticity: theoretical perspective and methodological consequences. *Restor. Neurol Neurosci.* 27, 375–389.

Zelazo, P. D. (2004). The development of conscious control in childhood. *Trends Cogn. Sci.* 8, 12–17.

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Can task-switching training enhance executive control functioning in children with attention deficit/-hyperactivity disorder?

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The key cognitive impairments of children with attention deficit/-hyperactivity disorder (ADHD) include executive control functions such as inhibitory control, task-switching, and working memory (WM). In this training study we examined whether task-switching training leads to improvements in these functions. Twenty children with combined type ADHD and stable methylphenidate medication performed a single-task and a task-switching training in a crossover training design. The children were randomly assigned to one of two groups. One group started with the single-task training and then performed the task-switching training and the other group vice versa. The effectiveness of the task-switching training was measured as performance improvements (relative to the single-task training) on a structurally similar but new switching task and on other executive control tasks measuring inhibitory control and verbal WM as well as on fluid intelligence (reasoning). The children in both groups showed improvements in task-switching, that is, a reduction of switching costs, but not in performing the single-tasks across four training sessions. Moreover, the task-switching training lead to selective enhancements in task-switching performance, that is, the reduction of task-switching costs was found to be larger after task-switching than after single-task training. Similar selective improvements were observed for inhibitory control and verbal WM, but not for reasoning. Results of this study suggest that task-switching training is an effective cognitive intervention that helps to enhance executive control functioning in children with ADHD.

Keywords: ADHD, task-switching training, executive control, training transfer

INTRODUCTION

The main goal of the present study was to determine the range of plasticity in executive control functioning in children with attention deficit/-hyperactivity disorder (ADHD). Executive control can be defined as a set of higher-order cognitive functions that organize and regulate goal-directed behavior including processes of planning, interference control, working memory (WM), task-switching, and task coordination (e.g., Miyake et al., 2000). Behavioral deficits observed in children with ADHD are characterized by inattention, impulsivity, and hyperactivity (American Psychiatric Association, 1994), and it has been suggested that those deficits are primarily related to executive control impairments, such as inhibitory control and WM (Barkley, 1997; Willcutt et al., 2005).

One experimental task that has frequently been applied in recent years to examine executive control functioning is the task-switching paradigm (for a recent review; Kiesel et al., 2010). The advantage of this paradigm is that it allows the separation of different components of executive control, such as task-set selection and maintenance, task-set switching, and interference control (Cepeda et al., 2001). In this type of task, the participants are usually instructed to switch between two simple cognitive tasks. For example, the participants are presented ambiguous stimuli, such as a series of digits varying in number and value (1, 3, 111, 333). In one task (task A), they have to decide whether the value of digits is one or three, and in the other task (task B), whether the number of digits is one or three. Performance can be measured in mixed-task blocks, in which the participants have to switch between both tasks A and B on every second trial, and in single-task blocks, in which only one of the tasks (A or B) has to be performed (Kray and Lindenberger, 2000; Kray et al., 2008). This allows the determination of two types of performance costs associated with the switching situation: mixing costs are defined as the difference in mean performance between mixed-task and single-task blocks and are assumed to refer to the ability to maintain two task sets and select between them. Switching costs are defined as the difference in mean performance between switch and non-switch trials within mixed-task blocks and they are assumed to measure the ability to flexibly switch between tasks (cf. Kray and Lindenberger, 2000; Kray et al., 2008). Finally, the efficiency of interference control can be measured by comparing the performance on congruent trials (in which the number and value decisions are not conflicting, i.e., 1, 333) with performance on incongruent trials (in which the number and value decisions are conflicting, i.e., 3, 111), that is, interference costs can be defined as the difference in mean performance between incongruent trials and congruent trials.

Cepeda et al. (2000) examined switching and interference costs in ADHD children (6–12 years old), on and off medication, in comparison to children without ADHD that were matched by age and IQ. Results of this study revealed that only ADHD children off medication showed larger switching costs and interference costs than healthy controls but there were no performance differences in these costs between ADHD children on medication and the control children. Moreover, switching costs in ADHD children off medication were only larger on incongruent trials, suggesting that children with ADHD particularly had problems to inhibit irrelevant task information when switching from one task to the other one (Kramer et al., 2001).

Given that children diagnosed with ADHD usually achieve lower academic degrees compared to equally cognitively able children without ADHD, and also have major problems in everyday functioning until adulthood (Rasmussen and Gillberg, 2001), the question of effective treatments, such as cognitive training interventions that help to improve executive control functioning, is of high relevance. One desirable feature of cognitive training interventions is that the training program does not only result in an improvement on the trained task, but that it also transfers to tasks that were not part of the training intervention (Lövdén et al., 2010). To determine the scope of transfer, we distinguish between near and far transfer. Near transfer refers to a generalization of training-related improvements to a new but structurally similar transfer task (e.g., transfer of task-switching training to another switching task, Karbach et al., 2010; Minear and Shah, 2008), while far transfer refers to dissimilar theoretical constructs (e.g., transfer of task-switching training to a WM task; cf. Karbach and Kray, 2009).

In a recent lifespan study, we investigated near and far transfer of task-switching training in children, younger, and older adults with a pretest–training–posttest design (Karbach and Kray, 2009). Pretest and posttest consisted of a cognitive test battery including several tests measuring task-switching (near transfer), interference control, verbal and visual WM, and fluid intelligence (far transfer). Importantly, we included an active control group in this study. Transfer was defined as relative performance improvements at posttest in the treatment group (task-switching training) as compared to the control group (single-task training). Note that both groups performed the identical number and type of A and B tasks, but the control group performed them in separate blocks (single-task training), while the training group switched between both tasks on every second trial (task-switching training). Results indicated that (a) all three age groups showed near transfer effects, that is, a larger reduction of mixing and switching costs from pretest to posttest in the training group than in the control group; (b) near transfer effects were more pronounced in children and older adults than in younger adults; and (c) far transfer effects were observed in all age groups, that is, performance improvements in interference control, verbal and visual WM, and fluid intelligence. The effect sizes for the group of children were between $d' = 1.2$–2.1 for near transfer and $d' = 0.5$–0.9 for far transfer of task-switching training. Given these promising effects of the cognitive training intervention in healthy children, the specific aim of the present study was to examine whether the training is of similar effectiveness in a group of children with substantial impairments in executive control.

There are a few studies demonstrating that training of executive control in children with ADHD leads to near as well as far transfer effects. Klingberg et al. (2002, 2005) used an adaptive training procedure including visuospatial and verbal WM tasks. They found performance improvements not only on the trained visuospatial WM task but also on non-trained tasks assessing visual–spatial memory, fluid intelligence (the Raven's), and interference control. More recently, Shalev et al. (2007) applied an attentional training program in order to improve school performance (e.g., math exercises, reading comprehension) and behavior (parents' self-reports of ADHD symptoms) in ADHD children (6–13 years old). The attentional training included the practice of sustained and selective attention, orienting of attention, and executive attention. The authors found training-related improvements in school performance as well as a reduction of inattention symptoms reported by the parents. Although these far transfer effects are impressive, it should be noted that the authors did not report the improvements on the trained tasks and they did not measure near transfer effects. Kerns et al. (1999) used a similar attentional training including seven ADHD children (7–11 years old) and reported far transfer effects to a number of attentional tasks that were not trained during the intervention.

The main goal of the present study was to determine the transfer scope after task-switching training in ADHD children. Therefore, we investigated near and far transfer effects of this training, similar to a previous study (Karbach and Kray, 2009). For ethical reasons (see also Procedure), we applied a crossover training design so that all ADHD children performed the cognitive intervention (i.e., the task-switching training) that has already been shown to enhance executive control functioning in healthy young children. However, they received the treatment at different times during the training protocol. That is, after performing the pretest, the children were randomly assigned to one of two groups: group 1 first performed the single-task training followed by posttest 1 and then the task-switching training followed by posttest 2 (see **Table 1**). Group 2 first performed the task-switching training as well as the first posttest and then the single-task training and the second posttest.

On the basis of previous results showing near and far transfer effects of WM and attentional control training in children with ADHD (Klingberg et al., 2002, 2005; Shalev et al., 2007) as well as near and far transfer effects of task-switching training in healthy young children (Karbach and Kray, 2009), we expected treatment-specific effects in this study. In particular, we predicted a larger reduction of mixing and switching costs after the treatment (task-switching training) than after the single-task training (near transfer) as well as larger improvements in executive control and fluid intelligence measures (far transfer). That is, group 2 should show larger performance improvements from pretest to posttest 1 as compared to group 1, and group 1 should show larger improvements from posttest 1 to posttest 2 than group 2. Given that far transfer effects are usually the smaller the less similar the training and the transfer tasks are, we also expected larger effect sizes for near than for far transfer.

MATERIALS AND METHODS

PARTICIPANTS

Thirty children were recruited for this study. Ten participants had to be excluded from the analysis because they were not willing to finish the training study ($n = 7$) or went off medication during the study ($n = 3$). Given that ADHD is more common in boys than girls (Froehlich et al., 2007), we included only male children. The final sample consisted of 20 boys that were randomly assigned to one of the two training conditions (group 1: $n = 10$, group 2: $n = 10$). Both groups were comparable in terms of age ($p = 1.00$; group 1: range = 8.7–12.1 years; group 2: range = 7.7–11.6 years) and IQ ($p = 0.44$). The severity of the ADHD-related symptoms was assessed by means of the German parent rating scale FBB–HKS (Döpfner and Görtz-Dorten, 2008). The questionnaire is based on the DSM-IV and ICD-10 criteria for ADHD and hyperkinetic disorders and allows the assessment of behavioral symptoms on the four scales (1) severity of inattention, (2) severity of hyperactivity/impulsivity, (3) generalized inattention problems, and (4) generalized hyperactivity/impulsivity problems. We found no between-group differences on any of the four scales (all $ps > 0.53$). Means and SD for age, IQ, and parent ratings are provided in **Table 2**.

All participants were enrolled in mainstream elementary and secondary schools. Prior to the inclusion into the study, they had been diagnosed according to the guidelines of DSM-IV (American Psychiatric Association, 1994) at the Department of Child and Adolescent Psychiatry, Saarland University Hospital, Germany. The diagnosis was based on a structured interview (K-DIPS, Unnewehr et al., 1998), an intelligence assessment (WISC-IV, Petermann and Petermann, 2007), and standard rating scales (such as the FBB–HKS, Döpfner and Görtz-Dorten, 2008) administered by expert physicians and psychologists.

After being diagnosed, the children had been medicated with methylphenidate. Although individual doses varied as a function of body weight and severity of the symptoms, most of the boys ($n = 18$) were prescribed 10–20 mg/day and two older children (10–11 years of age) up to 40 mg/day. Prior to the inclusion into the study, an independent physician assessed the effectiveness of the medication.

In sum, we applied the following inclusion criteria: (a) diagnosis of ADHD combined subtype, (b) age between 7 and 12 years, (c) stable long-term medication (methylphenidate), and (d) an IQ > 80 as measured with the Kaufmann Assessment Battery for Children (K-ABC; Melchers and Preuß, 1991). Exclusion criteria were (a) maternal drug abuse in pregnancy, (b) premature birth (<32 weeks) and low birth weight (<2000 g), (c) enrollment in special education settings, (d) neurological or chronic internal diseases, (e) Autism Spectrum, psychotic, bipolar, severe anxiety, and depressive disorder, and (f) any treatment with psychotropic drugs besides methylphenidate. The ethics review board of the Saarland Medical Association approved this training study. Written informed consent was given by one of the parents for all participating children. Subjects were paid 60 EUR for participating in the study.

Table 1 | Outline of the training protocol.

Pretest session 1	Training sessions 2–5	Posttest 1 session 6	Training sessions 7–10	Posttest 2 session 11
BOTH GROUPS	**GROUP 1**	**BOTH GROUPS**	**GROUP 1**	**BOTH GROUPS**
Single-tasks (tasks A and B)	Single-task training	Single-tasks (tasks A and B)	Task-switching training	Single-tasks (tasks A and B)
Task-switching (tasks A and B)	(tasks C and D)	Task-switching (tasks A and B)	(tasks C and D)	Task-switching (tasks A and B)
COGNITIVE BATTERY	**GROUP 2**	**COGNITIVE BATTERY**	**GROUP 2**	**COGNITIVE BATTERY**
Stroop task	Task-switching training	Stroop task	Single-task training	Stroop task
Verbal working memory	(tasks C and D)	Verbal working memory	(tasks C and D)	Verbal working memory
Fluid intelligence		Fluid intelligence		Fluid intelligence
Control measures		Control measures		Control measures
Demographic questionnaire				

Table 2 | Mean (SD) age, IQ, and sum scores on the FBB–HKS parent rating scale as a function of group at pretest.

	Group 1 (single-task training first)		Group 2 (task-switching training first)	
	M	**SD**	***M***	**SD**
Age	10.1	1.2	10.1	1.3
IQ	107	14	103	11
FBB–HKS: severity of inattention	13.8	4.6	14.4	7.7
FBB–HKS: severity of hyperactivity/impulsivity	15.2	7.4	13.7	5.4
FBB–HKS: generalized inattention problems	14.3	5.5	12.8	6.2
FBB–HKS: generalized hyperactivity/impulsivity problems	9.9	5.0	9.0	5.5

FBB–HKS scores are based on 20 items describing behavioral problems associated with ADHD and its subjective experienced severity. Parents were to rate the statements on a scale from 0 (not at all) to 3 (very much). Higher values correspond to more severe symptoms.

PROCEDURE

For ethical reasons, all children in this study performed the training intervention (i.e., the task-switching training) but at different times during the training protocol. Therefore, transfer of task-switching training was assessed by means of a pretest–training–posttest 1–training–posttest 2 design (see **Table 1**). To determine the transfer scope, the pretest and posttest sessions consisted of a structurally similar, but new switching task and a battery of several cognitive tasks that are assumed to measure executive control as well as fluid intelligence. All training conditions included four sessions, each of them lasting about 30–40 min. The training protocol was carried out over a time period of 11 weeks, that is, the children performed approximately one session per week, similar to the training protocol of our previous training study (Karbach and Kray, 2009). Three expert experimenters (one psychologist and two research assistants) administered the tests and experimental tasks. They were randomly assigned to the test sessions.

Pretest and posttest assessment

Task-switching. We used the same task-switching paradigm as in one of our previous training studies (cf. Karbach and Kray, 2009). In this type of paradigm, the participants worked through single-task blocks (i.e., performing task A or B only) and through mixed-task blocks requiring the switching between both tasks A and B on every second trial. Participants received no task cues and had to keep track of the task sequence. In task A, participants were to decide whether a picture showed a fruit or a vegetable ("food" task), and to respond by pressing a left or right response key, respectively. In task B, they were to decide whether the picture was small or large ("size" task) and they also responded with a left or right response key. The same two response keys were used for both tasks and all stimuli were ambiguous. Stimuli consisted of 16 fruit and 16 vegetable pictures and each one of them was presented in a large and a small version.

Children first performed two single-task practice blocks (each consisting of 17 trials) and then worked through 20 experimental blocks (8 single-task and 12 mixed-task blocks, each consisting of 17 trials). The order of blocks was random with the constraint that two single and two mixed-task blocks were grouped together. At the beginning of each trial, a fixation cross appeared for 1400 ms, followed by the target that was presented until the subject responded. After 25 ms, the next fixation cross appeared. The children were instructed to respond as fast and as accurately as possible. After each block, subjects received feedback about their mean speed and accuracy of responding.

Cognitive test battery. The cognitive test battery included several experimental tasks and tests measuring executive control (inhibitory control, verbal working memory) and fluid intelligence. The pre- and post-test assessment took about 60–70 min.

We applied a modified version of the "Color-Stroop Task" (Stroop, 1935). In this version, children were shown words (e.g., "red," "tree") presented in red, blue, green, or yellow font successively on the computer screen. The color words were presented either in the congruent color or in an incongruent color. Children were to indicate the color of the words as quickly as possible by pressing one of four response buttons. Participants first performed two practice blocks (à 12 trials) and then four experimental blocks (à 24 trials). Stimuli were presented until the subject responded or for a maximum of 2000 ms. The time window between the response and the next stimulus was 700 ms. The Stroop interference effect was defined as the difference in mean performance between incongruent and congruent trials.

Verbal WM was assessed with the test "Digit Sorting" (cf. Kray and Lindenberger, 2000). In this test, the experimenter read aloud a series of digits ranging in value from 1 to 20. The participants were to repeat the digits by sorting them in numerical order. The number of digits in each series varied between three and seven. Children first performed three practice series à three digits. The test started with three series à three digits, and then the number of digits per series was increased by one after each third series. The task was aborted after three consecutive erroneous responses. The test score was the number of correctly solved items.

We applied the matrix reasoning test from the German version of the Wechsler Intelligence Scale for Children (WISC-IV; Petermann and Petermann, 2007). In this test, the children were presented with a partially filled grid and asked to select the item that properly completed the matrix. Participants first completed three practice items, followed by up to 35 test items. The task was aborted after four consecutive erroneous responses or if four out of five consecutive items were not successfully completed. The test score was the number of correct responses.

In addition, we included two control measures on which we expected no positive transfer of the switching training. As a measure of perceptual speed of processing, we applied the Digit–Symbol Substitution test (Wechsler, 1982). Children saw a template containing nine digit–symbol mappings on the top of the page. Below, they saw 100 digits without the corresponding symbols. They were instructed to fill in the correct symbols as fast as possible. The test score was the number of correctly completed symbols after 90 s. As a measure of semantic knowledge, we used the Spot-a-Word test (Lehrl, 1977). In this test, 35 items are presented successively on the computer screen. Each item contains one correct word and four non-words. The participants were asked to find the one correct word. The test score was the number of correctly identified words.

The order of cognitive tasks and tests was constant during pre- and post-test assessment and were applied in the following order: Digit–Symbol Substitution Test, Task-Switching, Color-Stroop Task, Digit Sorting, Wechsler Intelligence Scale, and Spot-a-Word Test.

Training intervention. In the single-task training sessions, the children performed single-task blocks including either task C or task D. In the task-switching training sessions, the participants performed mixed-task blocks, that is, they were instructed to switch between both tasks C and D on every second trial. The experimental procedure during the training intervention was identical to the one applied at pretest and posttest except that children performed different tasks (tasks C and D). In task C ("transportation" task), subjects were to decide whether the pictures showed planes or cars, and in task D, ("number" task) whether one or two planes/cars were presented. They started with two practice blocks (à eight trials) followed by 24 experimental blocks (à 17 trials). In single-task training sessions, the children also started with two practice blocks (à eight trials) and then performed 24 experimental blocks (à 17 trials; 12 blocks of task C; and 12 blocks of task D in an alternating sequence). Overall all children worked through 1696 training trials in each training condition.

DATA ANALYSIS

Analyses for the switching and the Color-Stroop tasks were focused on mean RT for correct responses. We also analyzed response accuracy (% errors) but consistent with previous data, we found no transfer of training (Karbach and Kray, 2009). Practice blocks and the first trial in each block were excluded from data analyses. For all remaining tasks of this study, the analyses were based on accuracy (number of correct responses). In order to test for between-group training effects, we run analyses of variance (ANOVA) with the between-subjects factor Group (group 1: single-task first, group 2: switching first). For the evaluation of transfer effects, we also calculated Cohen's d (Cohen, 1977), or the standardized mean difference in performance between pretest and posttests (Verhaeghen et al., 1992). That is, the pretest–posttest differences (for each of the two groups) were divided by the pooled SD for test occasions. We then corrected all d values for small sample bias using the Hedges and Olkin correction factor (d'; Hedges and Olkin, 1985).

RESULTS

TRAINING EFFECTS

To test for between-group differences in training-related benefits, we ran two ANOVAs, the first one for the single-task conditions and the second one for the task-switching conditions. **Figures 1A,B** show the latencies a function of Training Session (1–4) and experimental Group (group 1, group 2).

Single-task training

Training-related changes were analyzed with Group (group 1: single-task first, group 2: switching first) as between-subjects factor and Session (S1, S2, S3, S4) as within-subjects factor. Results showed a main effect of Session, $F(3, 54) = 5.65$, $p < 0.01$, $\eta_p^2 = 0.24$, with a quadratic slope, $F(1, 54) = 16.99$, $p < 0.001$, $\eta_p^2 = 0.49$, indicating that latencies increased from session 1 to sessions 2 and 3 but decreased again in session 4 (see **Figure 1A**). Neither the main effect of Group nor the interaction with Session was significant.

Task-switching training

The ANOVA including the between-subjects factor Group (group 1: single-task first, group 2: switching first) and the two within-subjects factors Session (S1, S2, S3, S4) and Trial Type (non-switch, switch) showed a main effect of Session, $F(3, 54) = 5.05$, $p < 0.01$, $\eta_p^2 = 0.22$, indicating that latencies decreased as a function of training, and a main effect of Trial Type, $F(1, 18) = 23.84$, $p < 0.001$, $\eta_p^2 = 0.57$ (switching costs). An interaction between Session and Trial Type indicated that switching costs were reduced as a function of training, $F(3, 18) = 4.21$, $p = 0.01$, $\eta_p^2 = 0.19$ (see **Figure 1B**). Neither the main effect nor the interactions with the factor Group reached significance (all $p > 0.46$).

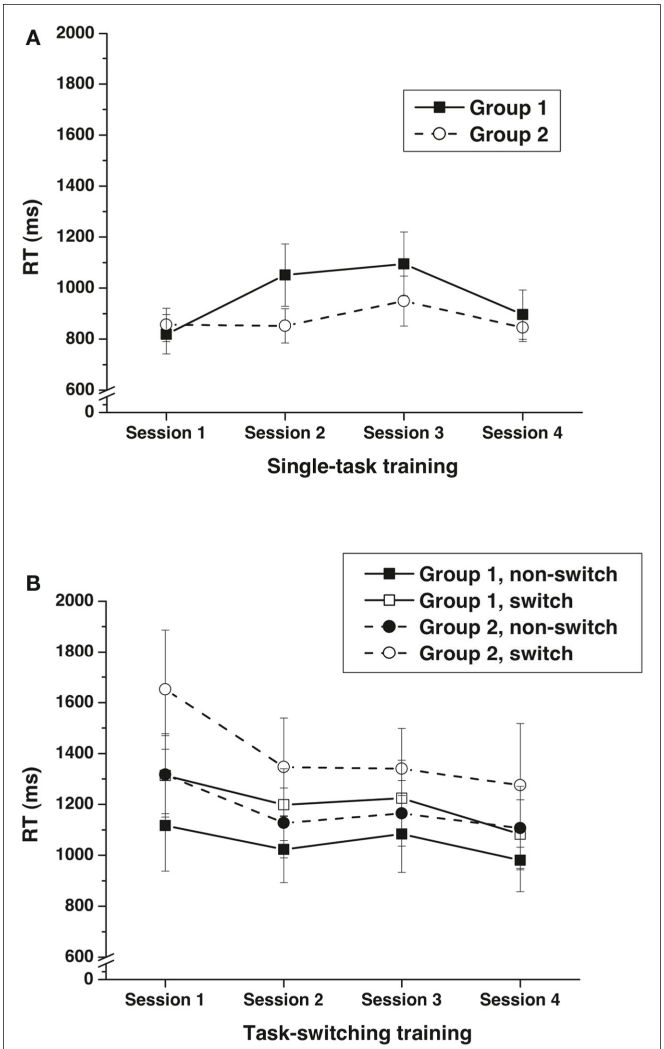

FIGURE 1 | Training: single-task (A) and task-switching (B) training performance as a function of group (group 1: single-task training first, group 2: task-switching training first) and training session (session 1–4). Error bars refer to SE of the mean.

ANALYSIS OF PRETEST DATA

In order to make sure that transfer effects were not confounded with pre-existing differences in baseline performance, we tested for between-group differences at pretest before analyzing near and far transfer. ANOVAs with the between-subjects factor Group (group 1, group 2) showed no significant group differences on any of the tasks (task-switching: $p = 0.65$, interference control: $p = 0.79$, verbal WM: $p = 0.66$, fluid intelligence: $p = 0.54$, perceptual speed: $p = 0.82$, semantic knowledge: $p = 0.65$).

NEAR TRANSFER EFFECTS

To investigate near transfer effects, we ran an ANOVA including the between-subjects factors Group (group 1: single-task first, group 2: switching first), and the within-subjects factors Trial Type (single, non-switch, switch), and Testing Time (pretest, posttest 1, posttest 2). As in previous studies (e.g., Kray and Lindenberger, 2000), mixing and switching costs were defined as two orthogonal contrasts. In the first contrast, the mean performance in single trials was tested against the mean performance on non-switch and switch trials (mixing costs), and in the second contrast mean performance on non-switch trials was tested against the mean performance on switch trials (switching costs). Training-specific effects were assessed by computing two contrasts for the factor Testing Time (pretest, posttest 1, posttest 2): The first contrast compared mean performance at pretest and posttest 1, and the second one compared mean performance at posttest 1 and posttest 2. The means and SD of all experimental conditions are shown in **Table 3**. Mixing and switching costs as a function of testing time for both groups are displayed in **Figures 2A,B**.

The overall ANOVA showed a main effect of Trial Type, $F(2, 36) = 41.55$, $p < 0.001$, $\eta_p^2 = 0.70$, revealing significant mixing costs and switching costs ($F(1, 18) = 35.42$, $p < 0.001$, $\eta_p^2 = 0.66$, and $F(1, 18) = 68.38$, $p < 0.001$, $\eta_p^2 = 0.79$, respectively). In addition, we found interactions between Trial Type and Testing Time, $F(4, 18) = 6.49$, $p < 0.001$, $\eta_p^2 = 0.27$, and Trial Type, Testing Time, and Group, $F(4, 18) = 3.51$, $p = 0.01$, $\eta_p^2 = 0.16$. Mixing costs were reduced from pretest to posttest 1, $F(1, 18) = 14.57$, $p < 0.001$, $\eta_p^2 = 0.45$. This reduction was somewhat larger for group 2 (task-switching training; $d' = 1.4$) than for group 1 (single-task training; $d' = 0.6$), $F(1, 18) = 3.40$, $p = 0.08$, $\eta_p^2 = 0.16$. Consistently, there also was a reduction of mixing costs from posttest 1 to posttest 2 in group 1 (task-switching training; $d' = 1.2$) but increased costs in group 2 (single-task training; $d' = -0.7$), $F(1, 18) = 6.64$, $p < 0.05$, $\eta_p^2 = 0.27$ (see **Figure 2A**).

Switching costs were also reduced from pretest to posttest 1, $F(1, 18) = 21.97$, $p < 0.001$, $\eta_p^2 = 0.55$. Although this effect was larger for group 2 (task-switching training; $d' = 2.6$) than for group 1 (single-task training; $d' = 1.0$), the interaction with group failed to reach significance ($p = 0.17$). The contrast between posttest 1 and posttest 2 showed a reduction of switching costs from posttest 1 to posttest 2 in group 1 (task-switching training; $d' = 0.4$) but an increase in group 2 (single-task training; $d' = -1.0$), $F(1, 18) = 5.02$, $p < 0.05$, $\eta_p^2 = 0.22$ (see **Figure 2B**).

FAR TRANSFER EFFECTS

We used a similar ANOVA design to examine far transfer effects of the training intervention. We first report the results on far transfer to other executive control tasks, that is, to interference control and verbal WM, followed by the findings on fluid intelligence (reasoning), and finally to the two control measures, speed of processing, and semantic knowledge. Data of all far transfer measures are shown in **Table 3**.

Interference control

Data were submitted to a three-way ANOVA with the factors Group (group 1: single-task first, group 2: switching first), Testing Time (pretest, posttest 1, posttest 2), and Trial Type (congruent, incongruent). We found a main effect of Testing Time, $F(2, 36) = 5.68$, $p < 0.01$, $\eta_p^2 = 0.24$, indicating that the participants responded faster at posttest 1 than at pretest ($p < 0.05$). The main effect of Trial Type pointed to reliable interference costs $F(1, 18) = 13.69$, $p < 0.01$, $\eta_p^2 = 0.43$, while the main effect

Table 3 | Mean performance (SD) for the near transfer (task-switching) and far transfer (inhibition, working memory, fluid intelligence) as a function of testing time (pretest, posttest 1, posttest 2) and group (group 1, group 2).

	Group 1 (single-task training first)						Group 2 (task-switching training first)					
	Pretest		Posttest 1		Posttest 2		Pretest		Posttest 1		Posttest 2	
	M	SD	*M*	SD	*M*	SD	*M*	SD	*M*	SD	*M*	SD
TASK-SWITCHING (NEAR TRANSFER)												
Single trials	1026	304	1106	414	1109	485	1080	272	1021	377	1027	397
Non-switch trials	1261	432	1303	559	1146	512	1355	480	1106	336	1255	722
Switch trials	1607	594	1487	641	1271	514	1715	480	1161	380	1503	869
Mixing costs	409	274	290	208	100	157	455	250	113	246	352	483
Switching costs	346	185	184	186	125	227	360	161	55	150	248	247
STROOP TASK (FAR TRANSFER)												
Congruent trials	899	205	843	163	788	99	859	235	836	221	840	230
Incongruent trials	952	219	900	186	825	127	939	214	823	170	836	182
Interference costs	53	46	57	67	38	61	80	48	−13	82	−4	86
WORKING MEMORY (FAR TRANSFER)												
Working memory	7.0	3.1	8.1	3.1	10.7	2.6	7.6	2.9	9.2	2.4	8.8	1.6
FLUID INTELLIGENCE (FAR TRANSFER)												
Fluid intelligence	21.9	4.9	23.3	2.8	23.3	4.8	20.4	5.7	20.7	4.7	21.4	3.1
CONTROL MEASURES												
Perceptual speed	32.4	8.7	37.4	9.4	38.6	10.2	31.3	12.0	36.5	11.6	36.6	11.2
Semantic knowledge	9.2	2.5	10.4	3.3	11.0	3.9	9.8	3.3	8.8	2.9	9.7	3.5

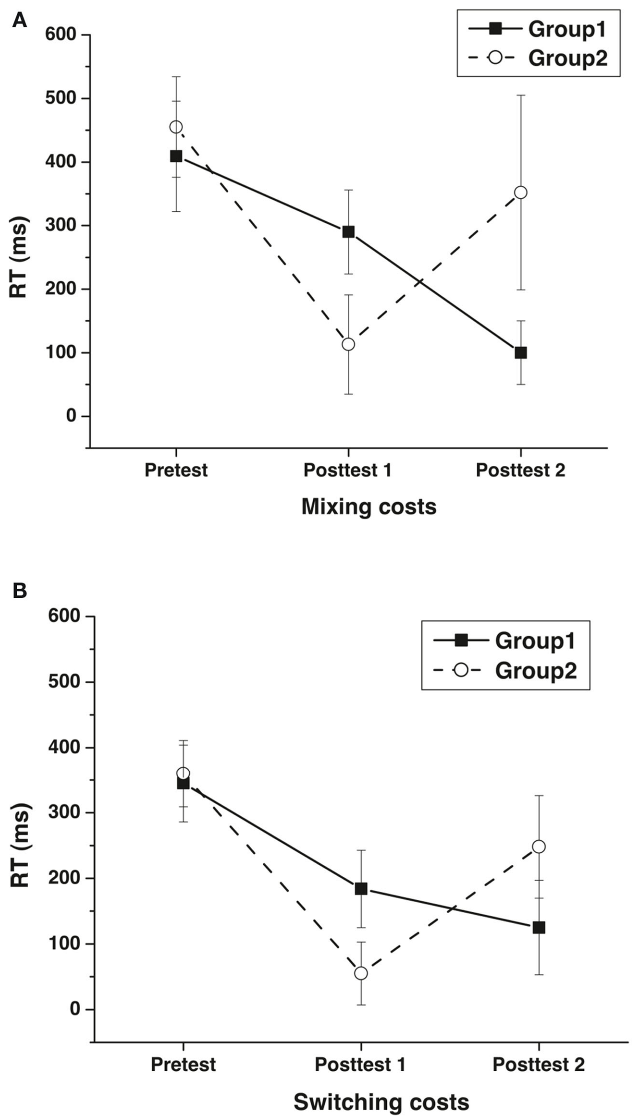

FIGURE 2 | Near transfer: mixing costs (A) and switching costs (B) as a function of group (group 1: single-task training first, group 2: task-switching training first) and testing time (pretest, posttest 1, posttest 2). Error bars refer to SE of the mean.

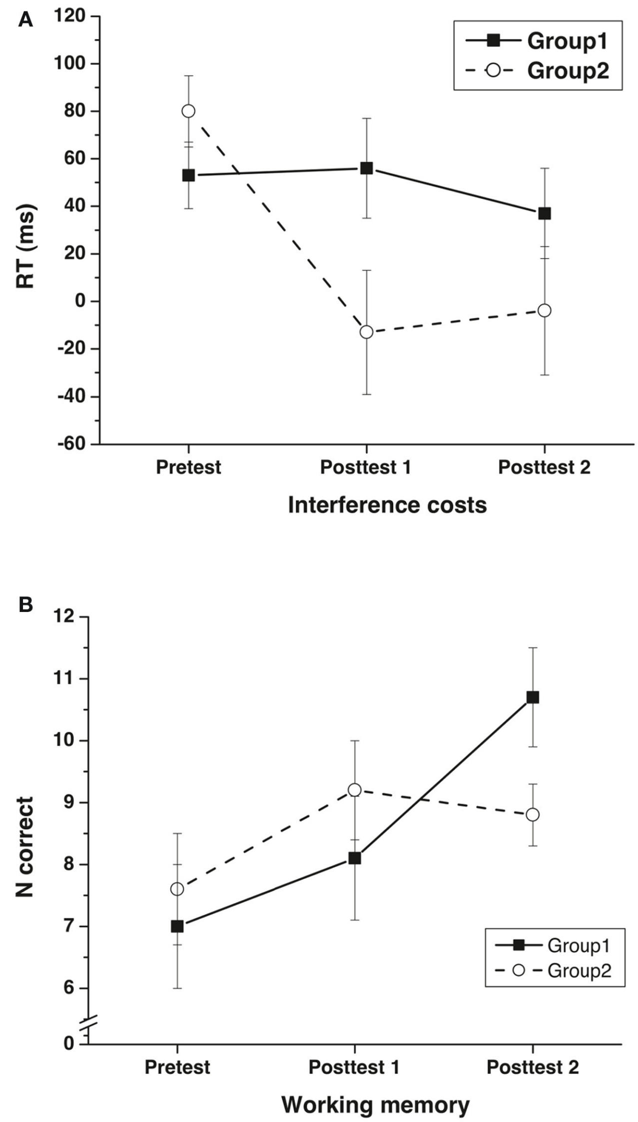

FIGURE 3 | Far transfer: interference costs (A) and working memory performance (B) as a function of group (group 1: single-task training first, group 2: task-switching training first) and testing time (pretest, posttest 1, posttest 2). Error bars refer to SE of the mean.

of Group failed to reach significance ($p = 0.88$). An interaction between Testing Time and Trial Type, $F(2, 36) = 3.80$, $p < 0.05$, $\eta_p^2 = 0.17$, revealed that interference costs were reduced from pretest to posttest 1, $F(1, 18) = 7.07$, $p < 0.05$, $\eta_p^2 = 0.28$. Importantly, we also found a marginally significant interaction between Testing Time, Trial Type, and Group, $F(2, 36) = 3.12$, $p = 0.06$, $\eta_p^2 = 0.15$. The contrast between pretest and posttest 1 showed that the reduction of interference costs was larger in group 2 (task-switching training; $d' = 1.6$) than in group 1 (single-task training; $d' = 0.1$), $F(1, 18) = 8.33$, $p = 0.01$, $\eta_p^2 = 0.32$ (see **Figure 3A**), but we obtained no larger reduction of interference costs in group 1 (task-switching training; $d' = 0.4$) than in group 2 (single-task training; $d' = 0.2$) from posttest 1 to posttest 2 ($p = 0.58$).

Verbal working memory

The ANOVA with the factors Group and Testing Time revealed a main effect of Testing Time, $F(2, 36) = 19.62$, $p < 0.001$, $\eta_p^2 = 0.52$, indicating that WM performance improved from pretest to posttest 1 and also from posttest 1 to posttest 2 (both $ps < 0.01$). The main effect of Group was not significant ($p = 0.95$). An interaction between Group and Testing Time, $F(2, 36) = 8.41$, $p < 0.001$, $\eta_p^2 = 0.32$, showed larger performance improvements from posttest 1 to posttest 2 in group 1 (task-switching training; $d' = 0.9$) than in group 2 (single-task training; $d' = -0.2$; see **Figure 3B**). However, no training-specific improvements were found from pretest to posttest 1 (single-task training: $d' = 0.3$; task-switching training: $d' = 0.6$; $p = 0.44$).

Fluid intelligence (reasoning)

The ANOVA with the factors Group and Testing Time neither revealed significant main effects nor an interaction (all $ps > 0.26$).

Control variables

The ANOVA based for perceptual speed of processing showed a main effect of Testing Time, $F(2, 36) = 15.61$, $p < 0.001$, $\eta_p^2 = 0.46$, with performance improvements from pretest to posttest 1 ($p < 0.001$), but neither the main effect for Group nor the interaction with Testing Time reached significance (both $ps > 0.77$). The analysis of the semantic knowledge task showed no significant effects (all $ps > 0.31$).

DISCUSSION

Children with ADHD showed a reduction of switching costs throughout the task-switching training, suggesting that they already benefited from a relatively short intervention of four training sessions. Even more important than the training-related improvements in switching performance are the near and far transfer effects observed in this study. As illustrated in **Figure 2A**, the task-switching training led to a substantial reduction of mixing costs in a similar switching task with similar effect sizes for the two groups (goup1: $d' = 1.4$; group 2: $d' = 1.2$), which can be considered as large effects (Verhaeghen et al., 1992). Interestingly, the treatment effect was about the same independently of whether the subjects had already performed the single-task training or not. In contrast, the task-switching training resulted in a large reduction of switching costs in the group that performed the task-switching training first (group 2: $d' = 2.6$), but the reduction in the group that had already performed single-task training was only very small (group 1: $d' = 0.4$), probably because there was not much room for improvement in task-switching (see **Figure 2B**). A similar pattern of findings occurs for the training-related changes in inhibitory control. While the group that performed the task-switching training first showed a substantial reduction of interference costs (group 2: $d' = 1.6$), this reduction was, however, only of small size for the group that had already performed the single-task training (group 1: $d' = 0.4$). We obtained a large increase in verbal WM in the group that performed the task-switching training first (group 2: $d' = 0.9$) while the effect size was only medium for the group that had already performed the single-task training (group 1: $d' = 0.6$). In contrast to our previous study with young children (Karbach and Kray, 2009), we did not find transfer of task-switching training to performance on a fluid intelligence test in children suffering from ADHD. However, it should be noted that we used different tests in both studies, which might explain the difference in findings.

In sum, the present study provided the first evidence for near and far transfer of task-switching training in children suffering from ADHD. It therefore is of major interest to examine whether the training was as effective in children with ADHD as it has previously been in healthy children. Comparing the results from the present study with our previous one (Karbach and Kray, 2009) showed that the effect sizes for the near transfer of task-switching were higher in healthy children than in the ADHD sample in terms of mixing costs (mean $d'_{\text{healthy group}} = 2.1$, mean $d'_{\text{ADHD group}} = 1.3$) but similar in terms of switching costs (mean $d'_{\text{healthy group}} = 1.2$, mean $d'_{\text{ADHD group}} = 1.5$). Regarding the far transfer to interference control, we even found slightly higher effects sizes in the ADHD group than in the healthy sample (mean $d'_{\text{healthy group}} = 0.5$, mean $d'_{\text{ADHD group}} = 0.8$), while the transfer to WM was comparable across studies (mean $d'_{\text{healthy group}} = 0.9$, mean $d'_{\text{ADHD group}} = 0.8$). Thus, the general pattern of results across both groups showed the typical finding of larger effect sizes on near compared to far transfer tasks. In addition, the size of these effects was similar (with the exception of mixing costs), indicating that results of the ADHD children seem to be within the range of what has been reported for healthy children. Although this finding has to be replicated within a single study, it points to the potential for the application of relatively short cognitive interventions in clinically relevant populations.

Although there was evidence for training-specific improvements of the task-switching intervention, it should be noted that we also obtained transfer effects of medium sizes after the single-task training. One possible explanation of this finding is that ADHD children have major deficits in the control of attention and interference. Given that the stimuli in this study were ambiguous, even the single-task training may have resulted in a certain amount of training in executive control. This means that although the ADHD children were not trained in task-switching, they may have been trained in focusing their attention on relevant information while ignoring irrelevant task features.

Although we found large effect sizes for near and far transfer of task-switching training, this study has some limitations. First, the sample was relatively small so that some interactions of the expected training-specific effects were only marginally significant. Second, the fact that we only investigated male children limits the generalizability of our findings. Third, given our training design, we also observed a decrease in task-switching performance between the posttest 1 and posttest 2 for the group that performed the single-task training after the task-switching training (group 2), as illustrated in **Figures 2A,B**. One possible explanation for this finding is that the ADHD children suffered from a loss of motivation across the four easier single-task training sessions and were therefore also less motivated to perform the switching tasks at posttest 2. Another explanation would be that the decrease in performance reflects negative transfer in the sense that the intensive training in performing single-tasks interferes with the coordination of control processes required for the switching tasks. Unclear is, however, why this negative effect does not occur for group 1. Either way future research is needed to clarify the nature of this carryover effect. If training order effects influence motivation, future studies could additionally control for individual differences in motivation and self-regulatory strategies such as self-efficacy or active engagement in the training. Such individual characteristics have recently been found to moderate memory training and transfer effects in elderly subjects (e.g., West and Hastings, 2011). As children with ADHD have impairments in regulating and maintaining engagement in an activity for a longer period of time, these motivational factors might also contribute to differential training and transfer effects in this clinical group.

The present training study extended our knowledge regarding useful cognitive training interventions for children with combined

ADHD who were on stable methylphenidate medication. Previous studies found that executive control functioning as well as academic skills and behavioral deficits can be improved by WM training and attentional control training (Kerns et al., 1999; Klingberg et al., 2002, 2005; Shalev et al., 2007). The intensity of the training was quite high in these studies [e.g., at least 25 training sessions in the Klingberg et al. (2005) study]. Results of our study suggest that performance improvements in executive control functioning can be achieved after a relatively short training intervention of four sessions in task-switching. However, whether even larger training effects can be achieved with adaptive or more intensive training procedures (Klingberg et al., 2002, 2005) and whether training effects can be maintained over a longer period of time has to be clarified in future studies. Another interesting question for future research with important clinical implications is to directly compare the effectiveness of the already existing training programs or to combine them in order to achieve an optimal cognitive intervention for children with ADHD.

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REFERENCES

American Psychiatric Association. (1994). *Diagnostic and Statistical Manual of Mental Disorders DSM-IV*. Washington, DC: American Psychiatric Association.

Barkley, R. A. (1997). Behavioral inhibition, sustained attention, and executive functions: constructing a unifying theory of ADHD. *Psychol. Bull.* 121, 65–94.

Cepeda, N. J., Cepeda, M. L., and Kramer, A. F. (2000). Task switching and attention deficit hyperactivity disorder. *J. Abnorm. Child Psychol.* 28, 213–226.

Cepeda, N. J., Kramer, A. F., and Gonzalez de Sather, J. C. (2001). Changes in executive control across the life span: examination of task-switching performance. *Dev. Psychol.* 37, 715–730.

Cohen, J. (1977). *Statistical Power Analysis for the Behavioral Sciences*. New York: Academic Press.

Döpfner, M., and Görtz-Dorten, A. (2008). *Diagnostik-System für Psychische Störungen im Kindes- und Jugendalter nach ICD-10 und DSM-IV (DISYPS-II)*. Bern: Huber.

Froehlich, T. E., Lanphear, B. P., Epstein, J. N., Barbaresi, W. J., Katusic, S. K., and Kahn, R. S. (2007). Prevalence, recognition, and treatment of attention-deficit/hyperactivity disorder in a national sample of US children. *Arch. Pediatr. Adolesc. Med.* 161, 857–864.

Hedges, L. V., and Olkin, I. (1985). *Statistical Methods for Meta-Analysis*. Orlando: Academic Press.

Karbach, J., and Kray, J. (2009). How useful is executive control training? Age differences in near and far transfer of task-switching training. *Dev. Sci.* 12, 978–990.

Karbach, J., Mang, S., and Kray, J. (2010). Transfer of verbal self-instruction training in older age: evidence from task switching. *Psychol. Aging* 25, 677–683.

Kerns, K. A., Eso, K., and Thomson, J. (1999). Investigation of a direct intervention for improving attention in young children with ADHD. *Dev. Neuropsychol.* 16, 273–295.

Kiesel, A., Steinhauer, M., Wendt, M., Falkenstein, M., Jost, K., Philipp, A. M., and Koch, I. (2010). Control and interference in task switching – a review. *Psychol. Bull.* 136, 849–874.

Klingberg, T., Fernell, E., Olesen, P., Johnson, M., Gustafsson, P., Dahlström, K., Gillberg, C. G., Forssberg, H., and Westerberg, H. (2005). Computerized training of working memory in children with ADHD – a randomized, controlled trial. *J. Am. Acad. Child Adolesc. Psychiatry* 44, 77–186.

Klingberg, T., Forssberg, H., and Westeberg, H. (2002). Training of working memory in children with ADHD. *J. Clin. Exp. Neuropsychol.* 24, 781–791.

Kramer, A. F., Cepeda, M. L., and Cepeda, M. L. (2001). Methylphenidat effects on task-switching performance in attention-deficit/hyperactivity disorder. *J. Am. Acad. Child Adolesc. Psychiatry* 40, 1277–1284.

Kray, J., Eber, J., and Karbach, J. (2008). Verbal self-instructions in task-switching: a compensatory tool for action-control deficits in childhood and old age? *Dev. Sci.* 11, 223–236.

Kray, J., and Lindenberger, U. (2000). Adult age differences in task switching. *Psychol. Aging* 15, 126–147.

Lehrl, S. (1977). *MWT-B: Mehrfach-Wahl-Wortschatz-Test B*. Erlangen: Straube.

Lövdén, M., Bäckman, L., Lindenberger, U., Scheafer, S., and Schmiedek, F. (2010). A theoretical framework for the study of adult cognitive plasticity. *Psychol. Bull.* 136, 659–676.

Melchers, P., and Preuß, U. (1991). *K-ABC: Kaufman Assessment Battery for Children*. Frankfurt: Swets & Zeitlinger.

Minear, M., and Shah, P. (2008). Training and transfer effects in task switching. *Mem. Cognit.* 36, 1470–1483.

Miyake, A., Friedman, N. P, Emersom, M. J, Witzki, A. H, Howerter, A., and Wagner, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: a latent variable analysis. *Cogn. Psychol.* 41, 49–100.

Petermann, F., and Petermann, U. (2007). *WISC-IV: Wechsler Intelligence Scale for Children – IV*. Bern: Huber.

Rasmussen, P., and Gillberg, C. (2001). Natural outcome of ADHD with developmental coordination disorder at age 22 years: a controlled, longitudinal, community-based study. *J. Am. Acad. Child Adolesc. Psychiatry* 39, 1424–1431.

Shalev, L., Tsal, Y., and Mevorach, C. (2007). Computerized progressive attentional training (CPAT): effective direct intervention for children with ADHD. *Child Neuropsychol.* 13, 382–388.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *J. Exp. Psychol.* 18, 643–662.

Unnewehr, S., Schneider, S., and Margraf, J. (1998). *Kinder-DIPS. Diagnostisches Interview bei psychischen Störungen im Kindes und Jugendalter*. Heidelberg: Springer.

Verhaeghen, P., Marcoen, A., and Goossens, L. (1992). Improving memory performance in the aged through mnemonic training: a meta-analytic study. *Psychol. Aging* 7, 242–251.

Wechsler, W. (1982). *Manual for the Hamburg-Wechsler Intelligence Test for Adults (HAWIE)*. Bern: Huber.

West, R. L., and Hastings, E. C. (2011). Self-regulation and recall: growth curve modeling of intervention outcomes for older adults. *Psychol. Aging* 26, 803–812.

Willcutt, E. G., Doyle, A. E., Nigg, J. T, Faraone, S. V., and Pennington, B. F. (2005). Validity of the executive function theory of attention deficit/hyperactivity disorder: a metaanalytic review. *Biol. Psychiatry* 57, 1336–1346.

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Plasticity of executive control through task switching training in adolescents

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Research has shown that cognitive training can enhance performance in executive control tasks. The current study was designed to explore if executive control, specifically task switching, can be trained in adolescents, what particular aspects of executive control may underlie training and transfer effects, and if acute bouts of exercise directly prior to cognitive training enhance training effects. For that purpose, a task switching training was employed that has been shown to be effective in other age groups. A group of adolescents (10–14 years, $n = 20$) that received a three-session task switching training was compared to a group ($n = 20$) that received the same task switching training but who exercised on a stationary bike before each training session. Additionally, a no-contact and an exercise only control group were included (both ns $= 20$). Analyses indicated that both training groups significantly reduced their switching costs over the course of the training sessions for reaction times and error rates, respectively. Analyses indicated transfer to mixing costs in a task switching task that was similar to the one used in training. Far transfer was limited to a choice reaction time task and a tendency for faster reaction times in an updating task. Analyses revealed no additional effects of the exercise intervention. Findings thus indicate that executive control can be enhanced in adolescents through training and that updating may be of particular relevance for the effects of task switching training.

Keywords: executive control, task switching, training, plasticity, transfer, sport, physical exercise, updating

INTRODUCTION

Executive control is the ability to plan, execute, and monitor goal-directed behavior (Norman and Shallice, 1986). It is a central neurocognitive process that is involved in a range of cognitive functions that are of everyday relevance, like problem solving or reasoning (Engle et al., 1999; Baddeley, 2003; van der Sluis et al., 2007). According to a model by Miyake et al. (2000) that has been derived empirically in adult and child populations (Lehto et al., 2003), executive control consists of different distinguishable components: maintaining and monitoring working memory representations (updating), deliberately suppressing prepotent responses (inhibition), and shifting between different tasks, or mental sets (set-shifting or switching).

There is a small, but growing body of promising research showing that executive control functions can be enhanced by systematic cognitive training with tasks requiring updating (Dahlin et al., 2008; Jaeggi et al., 2008), working memory (Klingberg et al., 2005; Holmes et al., 2009; Klingberg, 2010), task switching (Karbach and Kray, 2009), or dual task performance (Bherer et al., 2005; Liepelt et al., 2011). In addition to increases in performance on trained tasks, some of these studies were able to show transfer effects to non-trained tasks within the trained domain (e.g., working memory training transferred to complex working memory span tasks, Holmes et al., 2009) as well as to other executive control domains (e.g., inhibition tasks, Olesen et al., 2004; Klingberg et al., 2005; Karbach and Kray, 2009) or measures of non-verbal reasoning (Klingberg et al., 2005; Jaeggi et al., 2008). However, other studies have failed to find any transfer to similar tasks or suggest that transfer may be restricted to the trained domain (e.g., Dowsett and Livesey, 2000; Li et al., 2008; Strobach et al., in press). All of these studies have used a process-based training approach, where repeated performance on tasks, feedback, and often gradual adjustment of difficulty (Klingberg, 2010) implicitly leads to improvements.

Executive control training studies have targeted young (Jaeggi et al., 2008; Karbach and Kray, 2009) and older adults (Buschkuehl et al., 2008; Dahlin et al., 2008; Li et al., 2008; Zinke et al., 2012), as well as clinical populations of children, for example children with ADHD (Klingberg et al., 2005) or with low working memory abilities (Holmes et al., 2009). Evidence for training and transfer effects in typically developing children has only recently been accumulated (Karbach and Kray, 2009; Jaeggi et al., 2011; Loosli et al., 2012), whereas studies with older children and adolescents (especially above 12 years) are surprisingly very rare. This fact is rather remarkable because executive control processes are on the one hand highly relevant in the adolescents' daily life and school-related academic activities, e.g., reading or arithmetic (van der Sluis et al., 2007). Besides their ubiquitous relevance, executive control functions are on the other hand among the few functions that show development trajectories well into adolescence (Anderson, 2002; Huizinga et al., 2006) corresponding to relatively late maturation of prefrontal brain regions (Bunge et al., 2002; Luna et al., 2010). Recent studies suggest an ongoing development of different executive control functions across adolescence and even into young adulthood (Luna et al., 2004; Huizinga et al., 2006; Rubia et al., 2006). Taking these findings into account it appears straightforward to predict that the potential for plasticity through executive control training may be especially large in this age group. For that reason, it was the first aim of the current study to explore if an executive control training can also benefit cognitive functions in a population of adolescents.

With regard to executive control training, currently, one conceptual issue is especially under debate: does it matter what domain of executive control is being trained? The most consistent findings for executive control trainings have, so far, been achieved in a range of studies that train tasks requiring updating (e.g., Dahlin et al., 2008; Jaeggi et al., 2008, 2011) or working memory (Klingberg et al., 2005; Holmes et al., 2009; Loosli et al., 2012; see Klingberg, 2010 for a review). These studies have mostly found robust transfer to other working memory tasks and even some (but limited) far transfer to other executive control domains or reasoning (Klingberg et al., 2005; Jaeggi et al., 2011), and mathematical or reading performance (Holmes et al., 2009; Loosli et al., 2012). Much less consistent findings come from the few training studies employing inhibition tasks. One study was able to show transfer of an inhibitory control training to a non-trained inhibition task (Go/No Go, Dowsett and Livesey, 2000), whereas another study did not find any transfer to other executive control tasks (Thorell et al., 2009). With respect to the third facet of executive control, switching, the available literature is also scarce: although there are a range of studies showing practice-related improvements in task switching paradigms (Kramer et al., 1999; Buchler et al., 2008; Kray et al., 2008), fewer have explored transfer to other tasks. Those that have, report transfer to other switching tasks (Minear and Shah, 2008) or to other domains of executive control like working memory, inhibition, and reasoning (Karbach and Kray, 2009; Kray et al., 2010). Summarizing research on the different domains of executive functions, a broad range of findings in the updating domain suggest consistent training and transfer effects, whereas the very few findings for the inhibition domain are inconclusive and do not seem to be very promising. In contrast, the few findings from the task switching domain seem to be promising concerning the range of transfer effects, especially the study by Karbach and Kray (2009). For that reason, the current study aimed at training task switching abilities and closely modeled the training regime after the study by Karbach and Kray (2009). Extending that study which had targeted primary school children, young adults, and older adults, the current study aimed at exploring if similar effects of this particular task switching training can also be achieved in adolescents.

Task switching requires participants to switch from performing one (mostly) simple task (e.g., deciding whether a picture shows a vegetable or a fruit) to performing a second simple task (e.g., deciding whether an object is small or large) from trial to trial. Task switching paradigms usually involve single-task blocks where only one task has to be performed the whole time and mixed-task blocks where the participant has to switch between tasks. Switching to a new task is usually accompanied by costs (slower and more error-prone task execution). The literature distinguishes between mixing costs as the difference in mean performance between mixed-task and single-task blocks and switching costs as the difference in mean performance between switch and non-switch trials within mixed-task blocks (see, e.g., Karbach and Kray, 2009). These costs are thought to reflect different executive control processes. Mixing costs are thought to reflect a more global ability to maintain and select two different task sets, whereas switching costs reflect more specifically the actual act of switching from one task to the other (Kray and Lindenberger, 2000; Braver et al., 2003). With regard to task switching training, studies mostly report practice-related reductions in both types of costs during training (Cepeda et al., 2001; Kray et al., 2008). Studies comparing both types of costs suggest larger decreases (or even elimination) with training in mixing costs as compared to switching costs (Berryhill and Hughes, 2009; Strobach et al., 2012). Transfer has been found for mixing costs only (Minear and Shah, 2008) or both types of costs (Karbach and Kray, 2009).

What aspects of task switching are actually trained and may underlie the transfer to other switching or executive control tasks is not well understood. It has been suggested that different executive control processes are involved in switching from one task to the other. These include maintaining several task sets in working memory, selecting, and configuring the appropriate task set (as is thought to be indicated by mixing costs), or focusing attention on relevant aspects and inhibiting now irrelevant aspects of the stimulus or task set (as is thought to be indicated by switching costs, Kramer et al., 1999; Mayr, 2003; Minear and Shah, 2008). Thus, it is reasonable to assume that changes in some or all of the three facets of executive control may be of importance for the possible effects of task switching training. In line with this assumption, (Karbach and Kray, 2009) suggest that task switching training may not only improve task set selection, but also improve maintenance of goals (updating) and/or improve inhibitory control to suppress currently irrelevant features. Findings of transfer to mixing costs (Minear and Shah, 2008; Karbach and Kray, 2009) may point to the relevance of updating processes in mediating training and transfer effects, because mixing costs are thought to reflect the more global ability to maintain different task sets (Kray and Lindenberger, 2000; Braver et al., 2003). The involvement of inhibitory processes in task switching training effects may be inferred from transfer that has been found for an inhibition task (i.e., Stroop task, Karbach and Kray, 2009). However, the transfer tasks used in Karbach and Kray's study were not specifically chosen to tap all different domains of executive control – therefore, one cannot directly infer from their data which of the executive control domains may be specifically associated with the training and transfer effects. Following up on this issue, as a second aim, the current study was set up to systematically explore transfer to all three executive control domains, namely shifting (e.g., with a number switch task), updating (e.g., with an *n*-back task), and inhibition (e.g., with a Stroop task). Because effects may be different for speed and accuracy of responses (as may be inferred from differing developmental trajectories for reaction time, RT, and accuracy measures for executive control tasks, e.g., (Davidson et al., 2006), measures for both RTs and error rates were included.

A third open question addressed by the current study concerns the specific conditions under which executive control training is most effective. Besides the conceptual question of pathways leading to training and transfer effects, this question was also motivated by the applied aspect of how to implement training regimes best for adolescents. One possible contributing factor in this regard concerns the interplay of cognitive and physical activation as it can be found in school settings. Here, another line of research is relevant to consider that is concerned with the acute effects of physical exercise on cognitive functions (see for a review, Tomporowski, 2003). Most of these studies measure performance on different cognitive tasks during or right after the participants have exercised for a predefined time, for example on a treadmill or a stationary bicycle. Facilitating effects of acute exercise have been found repeatedly for basic information processing, for example increased speed in simple and more complex reaction time tasks (Hogervorst et al., 1996; Ellemberg and St-Louis-Deschênes, 2010). Results are more mixed for higher order functions like executive control functions. Studies have found effects of acute exercise on behavior and electrophysiological measures in tasks requiring inhibition (e.g., Stroop task, Hogervorst et al., 1996; Yanagisawa et al., 2010; Flanker task, Magnié et al., 2000; Hillman et al., 2009), working memory (Pontifex et al., 2009), and attention switching (Pesce et al., 2003). However, other studies have failed to find an influence on inhibition (Themanson and Hillman, 2006; Stroth et al., 2009) or mental set-shifting (Tomporowski et al., 2008). A recent meta-analysis by Lambourne and Tomporowski (2010) explored overall effects of acute exercise on cognitive functioning during and after exercise. Results suggest that facilitating effects can be found mostly after exercise and for speed in decision making tasks, memory, and executive functioning tasks.

Although these studies all relate to cognitive performance (not training) right after exercise, several authors such as Hillman et al. (2009) or McDaniel and Bugg (in press) have recently suggested that it may be valuable to look at effects of acute exercise on cognitive control or memory training, respectively. It could be speculated that acute exercise may facilitate or enhance neuronal change that may be induced by cognitive training. Also, if acute exercise directly enhances memory processes (see, e.g., Pesce et al., 2009; Lambourne and Tomporowski, 2010) it may impact learning during cognitive trainings. However, findings have not been consistent as to what cognitive functions are affected and when. Some findings even suggest detrimental effects of physical exercise on executive control functions during or right after exercise (e.g., Dietrich and Sparling, 2004; Dietrich, 2006). For these reasons, as an exploratory third research question, the current study aimed at evaluating the conceptual proposal (Hillman et al., 2009; McDaniel and Bugg, in press) of a possible added value of an acute bout of exercise prior to cognitive training sessions.

In summary, the aims of the current study were the following. The first central question was if executive control functions can be trained in adolescents – an age group where executive control functions are highly relevant and still developing. The study set out to explore whether and which particular training and transfer effects can be achieved in the domain of task switching in adolescents using the training by Karbach and Kray (2009). Specifically, transfer effects would constitute larger gains in performance from pre to posttraining in the task switching training groups as compared to the control groups. Furthermore, as the second aim, the study systematically explored possible transfer effects to all three main executive control facets suggested by Miyake et al. (2000) with RT and accuracy measures. Third, the current study is the first to empirically explore the recent proposition of possible favorable effects of acute bouts of exercise on cognitive control training. If acute bouts of exercise have a favorable effect, we would expect differences in the size of training and transfer effects depending on whether participants received prior acute bouts of exercise or not.

MATERIALS AND METHODS

PARTICIPANTS

The 80 participants of the study were adolescents aged between 10 and 14 years (mean age: 11.9, SD = 1.3). They were recruited in local schools and youth clubs and were reimbursed for their participation with four Euros per hour. All participants and parents received extensive oral and written information about the study. Only if parents and participants gave written informed consent adolescents were included into the study. The study was approved by the ethics committee of the German Society of Psychology. Each participant was individually assigned to one of four groups by randomly drawing group assignments. The study had a three-factorial design with two between-subjects factors, cognitive training (yes vs. no) and exercise intervention (yes vs. no), and one within-subject factor, time of measurement (pretraining vs. posttraining). Hence, there were two cognitive training groups: one combined training group (acute physical exercise right before each cognitive training) and one cognitive training only group; and two control groups: one exercise only control group (acute physical exercise) and a no-contact control group. The four groups of 20 participants were matched in age, gender, BMI, fitness, and basic cognitive functioning (see **Table 1**). The participants were free of any neurological, psychiatric or physical disorders, and did not take medication according to parents' reports. Baseline cognitive functioning was assessed with two tests. Verbal abilities were measured using the vocabulary subscale of the German adaptation of the Wechsler Intelligence Scale for children (WISC-IV, Petermann and Petermann, 2010), where children have to define words. Fluid abilities were assessed with the Digit Span subtest, where children

Table 1 | Participant characteristics of the training groups (with and without prior exercise) and the control groups (exercise only and no-contact, all *n* = 20).

Measure	Cognitive training groups		Control groups	
	With exercise *M* (SD)	No exercise *M* (SD)	Exercise only *M* (SD)	No-contact *M* (SD)
Gender	9 girls	9 girls	9 girls	9 girls
Age	11.9 (1.2)	11.9 (1.4)	11.8 (1.2)	11.9 (1.3)
BMI	18.0 (1.9)	19.5 (2.8)	18.2 (2.0)	18.1 (2.0)
Fitness in W/kg	3.0 (0.4)	3.0 (0.5)	2.9 (0.5)	2.9 (0.5)
Vocabulary	13.2 (2.3)	13.0 (2.8)	13.2 (3.0)	13.2 (2.7)
Digit span	10.9 (3.2)	10.0 (2.9)	11.0 (2.6)	9.9 (2.2)

have to repeat digit sequences of ascending length in the same or reverse order (Petermann and Petermann, 2010).

COGNITIVE TRAINING TASK

The cognitive training material was closely modeled after Karbach and Kray (2009). The participants' task was to switch as fast and accurately as possible between two simple tasks. The first task was to decide via key press, whether the picture presented was a car or a plane (vehicle task). The second task was to decide via key press whether there were one or two objects on the picture (number task). Both tasks were mapped onto the same keys (left key: "car" or "one"; right key: "plane" or "two") which were to be pressed with the left and the right index finger, respectively. Each training session consisted of two short practice blocks (8 trials each) and 24 mixed-task blocks consisting of 17 trials, each starting with a fixation cross (700 ms), followed by a picture until a response was made. Participants were told to switch between tasks on every second trial, that is to perform the vehicle task twice, then the number task twice, then the vehicle task twice again, and so on. At the beginning of each block, participants were reminded of the sequence and could start over new in case they lost track. During training, participants received a feedback after each block about how many trials they answered correctly and how fast they reacted. Additionally, several times during training, the experimenter verbally encouraged the participants to try to be even more accurate and/or answer faster. The main dependent variables were mean switching cost for RT data (mean RT switch trials – mean RT non-switch trials) and for errors (error rate switch trials – error rate non-switch trials).

ACUTE EXERCISE INTERVENTION

The physical exercise intervention was modeled after similar interventions in other acute exercise studies (e.g., Hillman et al., 2009; Stroth et al., 2009). Participants had to cycle on a stationary bike (Kettler, Model X3) for 20 min at about 60% of their individual maximal heart rate, a moderately intense physical exercise. Heart rate was monitored with POLAR heart rate monitors (Polar Electro, Model FT1) that send their measurements to the stationary bike. The stationary bike was set to a program that automatically adjusted resistance to help the participant stay in the target heart rate zone.

FITNESS ASSESSMENT

Fitness was assessed with a graded maximal exercise test on a stationary bike (Kettler, Model X3) following standards of the WHO to test fitness and a standardized protocol from large German study on fitness in children and adolescents (Bös et al., 2009). Difficulty of cycling started at a resistance of 25 W with watt-load being increased by 25 W every 2 min while the participant was asked to keep the pedaling rate above 60 rotations per minute. Heart rate was monitored with a POLAR heart rate monitor (Polar Electro, Model FT1) and testing was stopped if one of the prespecified stopping criteria was reached. These criteria were: (a) heart rate above 180 bpm for over 15 s, (b) the pedaling rate below 50 for more than 20 s, (c) report of subjective exhaustion, or (d) any sign of discomfort, pain, sudden changes in heart rate, etc. The main measure of physical fitness was maximal watt performance related to body weight (W/body weight in kg, following Bös et al., 2009).

TRANSFER TASKS

To assess transfer to different domains, a range of tasks were used in the current study. Tasks were chosen to cover the three domains of executive control (switching, updating, and inhibition) with tasks including picture or verbal stimuli. Furthermore, tasks were included to cover the speed domain that has been shown to be a relevant outcome variable in acute exercise research. Because effects may be different on the level of RT and accuracy, measures for both levels were included in each domain.

Task switching

To assess near transfer of task switching training, a task switching task was used that was structurally similar to the training task but included different pictures and tasks. The first task was to decide via key press, whether the picture shown was a fruit or a vegetable (food task). The second task was to decide via key press whether the picture was small or large (size task). Both tasks were mapped onto the same keys (left key: "fruit" or "small"; right key: "vegetable" or "large") which were to be pressed with the left and the right index finger, respectively. Participants were instructed on how to perform each single-task separately and had one practice block of 17 trials for each task. After that they were instructed for the mixed-task block: they were told to switch between tasks on every second trial, that is to perform the food task twice, then the size task twice, then the food task twice again, and so on. Thus, trials where participants had to switch and trials where they had to repeat the task alternated. The participants had two mixed-task blocks with 17 trials each to practice. After that there were 20 more blocks with either single-task performance (5 for vehicle task, 5 for number task) or mixed-task performance (10 blocks) with a reminder of the respective instruction at the beginning of each block. Each block consisted of 17 trials each starting with a fixation cross (1400 ms), followed by the picture until a response was made. Main dependent variables on a RT level were mixing costs (mean RT mixed-task blocks – mean RT single-task blocks) and switching costs (mean RT switch trials – mean RT non-switch trials). On the level of error data dependent variables were mixing costs (error rate in mixed-task blocks – error rate in single-task blocks) and switching costs (error rate in switch trials – error rate in non-switch trials).

Furthermore, a switching task with verbal material (numbers 1–4 and 6–9) was used: a number switch task[1] (see, e.g., Koch and Allport, 2006) where participants had to switch between judging whether the number presented on the screen was smaller or larger than five or whether it was even or odd. An external cueing paradigm was used (with a fixed CSI of 0 ms), that is the task to be executed was written above the stimuli ("smaller or larger than 5"? or "even or odd"?) and was present until a response was made. There was a blank interstimulus interval of 1000 ms in between trials. There were two single-task blocks of 40 trials each for the size task and the even/odd-task, respectively. Afterward participants

[1]In the traditional binary taxonomy of near and far transfer tasks, this number switch task is difficult to allocate, as it assesses the same construct as in training, i.e., task switching. However, because the paradigm is different, it may also require different cognitive functions. Therefore, this task could be considered at an intermediate level of transfer.

performed another block of 80 trials where tasks were randomly intermixed. That is, in approximately half of the trials participants had to switch between tasks, in the remaining trials they had to repeat the previous task. Main dependent variables were the same as in the other switching task, that is mixing and switching cost on the level of RT and error data, respectively.

Updating

As a measure of updating, an animal picture 2-back task was used. The participants were to decide if the animal presented was the same as the one next-to-last with a key press ("yes" if they were the same, "no" if they were not). Line drawings of animals (taken from Snodgrass and Vanderwart, 1980) were presented for 1500 ms each, followed by a 1000-ms blank interstimulus interval. After a short practice of seven trials, participants performed a block of 122 trials (the first two trials were excluded from the analyses because there is no next-to-last picture on these trials), 25% of the pictures were target pictures. Main dependent variables were mean RT for correct decisions and percentage of correct target hits.

As a measure of updating with verbal stimuli a keep track task following Miyake et al. (2000) was used. In this task, words (e.g., uncle) that belong to 6 different semantic categories (e.g., relatives) were presented for 1500 ms one after another. The participants were instructed to remember the last word presented from each target category and name them at the end of each trial. Six to fifteen words were presented in each of five trials and two to four categories were to be tracked in each trial. Target categories were shown on the bottom of the screen for the whole trial. Because several words from each target category were presented on each trial, correct responses required successful updating of working memory content during the trial. Main dependent measure was the percentage of words recalled correctly.

Inhibition

To assess inhibition, a version of a visual Flanker task following the classic paradigm by (Eriksen and Eriksen, 1974) was used. The participants had to decide via key press if the small target square presented in the middle of the screen was red or blue. Two larger, colored squares were presented simultaneously on each side of the small target square: either the same color as the target (congruent trials) or a different color (incongruent trials). After a practice block of 12 trials, participants worked on a block of 100 randomized trials, half of the trials congruent, half of them incongruent. Main dependent variable on the RT level was the difference in mean RTs between correct incongruent and congruent trials (interference score) and percentage of correct answers on the accuracy level.

The Stroop interference task (German version of the color-word-Stroop test taken from the Nürnberger Altersinventar, NAI, Oswald and Fleischmann, 1995) was used to measure inhibitory control with verbal material. Here, the participant first had to read out loud 36 color names (printed in black on a sheet) as fast as possible; in the second run the participant had to name 36 color patches; in the last run he/she had to name the print color of 36 color words printed in different colors. Overall time was taken for each run. The main dependent variable was the difference in overall naming time between the third and the second run (interference score)[2].

Speed

A simple reaction time task was used to assess speed in detection of visual stimuli. A white circle was presented in the middle of the screen with a variable time interval of 1000–2000 ms in between. The participant was to press a key as fast as possible whenever a circle appeared. The circle disappeared at the time of key press. After a practice block of 10 trials, participants worked on a test block of 50 trials. Dependent variable was the mean RT.

A choice reaction time task was used to assess speed in simple decision making. A white arrow, either pointing to the right or the left, was presented in the middle of the screen with a variable time interval of 1000–2000 ms in between. The participant was to press the left arrow key as fast as possible whenever a left-pointing arrow appeared and the right arrow key whenever a right-pointing arrow appeared. The arrow disappeared at the time of key press. After a practice block of 10 trials, participants worked on two test blocks of 54 trials each. Dependent variable was the mean RT on correct trials and percentage of correct decisions.

PROCEDURE

All adolescents participated in a pretraining and a posttraining assessment, where performance in transfer tasks was assessed with parallel versions, respectively. The order of tasks was held constant in all assessments. Testing started with speed tasks, followed by the near transfer switching task, 2-back task, Flanker task, and digit span. After a 5-min break, testing continued with the number switch task, track task, Stroop task, and fitness assessment in the pretest session and vocabulary in posttest session.

Pretraining and posttraining sessions were scheduled in week one and five for each participant. In weeks two to four, participants of the two training groups and the exercise group had three training/exercise sessions, the no-contact control group did not have any sessions. These training sessions were scheduled with up to three adolescents at the same time and lasted for about 20–25 min for the cognitive training group and the exercise only control group and 45 min for the combined training group.

RESULTS

Prior to RT data analyses, for the switching tasks, trials that had RTs faster than 100 ms or longer than 4000 ms were excluded (following Karbach and Kray, 2009). For 2-back, Flanker, and speed tasks all trials with RTs faster than 100 ms and slower than 1500 ms were excluded prior to analyses. Excluded trials were counted as errors in the analyses of accuracy data.

TRAINING GAINS IN TRAINED TASKS

The first set of analyses was conducted with the two training groups to answer the first and third research question: if task switching can be improved in adolescents via cognitive training and if prior physical exercise influences training gains. To test for

[2]Because error rates are generally extremely low in this task (mean error rate was below 1% in the current study, see **Table 4**), only RT data serves as dependent variable.

significant performance changes over the course of the training days and possible differences between the training groups with and without additional exercise intervention, separate repeated measures ANOVAs were conducted for RT and error data. Training group (cognitive training vs. combined training) served as between-subjects factor and time of measurement (training days) as the within-subject factor.

For the RT data, analyses revealed a significant main effect of time for switching costs, $F(1.6, 61.5) = 25.9$, $p < 0.001$, partial $\eta^2 = 0.41$ (Greenhouse-Geisser corrections for lack of sphericity were applied), indicating that both training groups showed reductions of RT switching costs over the course of all training days (see **Figure 1**). Neither the main effect of training group nor the interaction term (Time × Training group) reached significance, indicating that training groups neither differed in their RT switching costs overall nor in their reduction of switching costs over training. An additional dependent t-test for paired samples revealed that mean reductions in RTs from the first training day to the last training day (see **Table 2** for complete mean RT and error data) were larger for switch trials, $M = -241.5$ ms, $SD = -145.9$, corresponding to a reduction of about 25%, than for non-switch trials, $M = -136.1$ ms, $SD = -84.1$, corresponding to a reduction of about 18%, $t(39) = 6.6$, $p < 0.001$. Reduction rates did not differ significantly between the two training groups. This indicates that participants of both training groups showed larger improvements in RT on switch trials than on non-switch trials.

For the accuracy data, analyses revealed a significant effect of time for switching costs, $F(2, 76) = 9.3$, $p < 0.001$, partial $\eta^2 = 0.20$, indicating that all trained participants showed reductions of error switching costs over the course of training days (see **Figure 1**). Neither the main effect of training group nor the interaction term (Time × Training group) reached significance, indicating that training groups neither differed in their error switching costs overall nor in their reduction of error switching costs over training. An additional dependent t-test for paired samples revealed that error rates for non-switch trials increased from the first training day to the last training day, $M = 3.2\%$, $SD = 6.5$, whereas error rates for switch trials did not change, $M = 0.4\%$, $SD = 6.9$, $t(39) = 3.8$, $p < 0.001$ (see **Table 2** for complete mean RT and error data). Changes in error rates did not differ significantly between the two training groups.

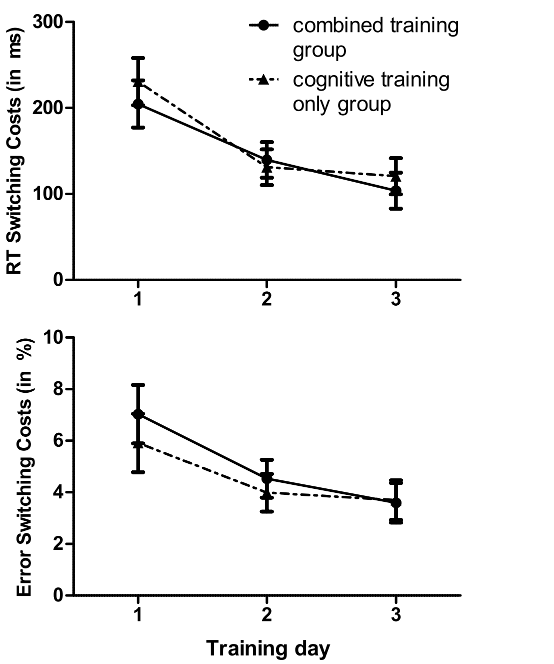

FIGURE 1 | Trajectories of RT switching costs (mean switching costs in ms ± SE) and error rate switching costs (mean switching costs in % ± SE) in the training task over the course of the three training days in the combined training group and the cognitive only training group.

TRANSFER EFFECTS OF TASK SWITCHING TRAINING TO NON-TRAINED TASKS

The second set of analyses was conducted with all participants to answer the second and third research question, that is what specific transfer effects can be found in adolescents after task switching training and if prior exercise influences transfer effects. To explore performance changes in transfer tasks between the pretraining and posttraining assessments, differences between the cognitive training and control groups, and possible differences between exercise and no exercise groups, two separate three-factorial MANOVAs were conducted for RT data (switching and mixing costs, RT, and interference scores) and error data (error rate switching and mixing costs and accuracy rates) in the transfer tasks. Cognitive training (training vs. no training) and exercise intervention (exercise vs. no exercise) served as between-subjects factors and time of measurement (pretraining vs. posttraining) as the within-subject factor. To account for multiple comparisons, we first looked at effects of the three factors on the combined dependent variables of RT and accuracy transfer measures, respectively. If the multivariate analyses were significant, separate follow-up ANOVAs were

Table 2 | Mean RT and error data for task switching training task in all three training sessions for the combined and the cognitive training only group.

	Training session 1 *M* (SD)	Training session 2 *M* (SD)	Training session 3 *M* (SD)
COMBINED TRAINING GROUP			
mean RT in ms			
Non-switch trials	718 (182)	638 (233)	576 (162)
Switch trials	949 (301)	769 (244)	697 (247)
Error rate in %			
Non-switch trials	10.5 (7.9)	12.3 (7.5)	12.9 (9.2)
Switch trials	16.4 (9.4)	16.3 (9.2)	16.6 (8.2)
COGNITIVE TRAINING ONLY GROUP			
mean RT in ms			
Non-switch trials	726 (131)	636 (105)	596 (93)
Switch trials	931 (199)	776 (199)	700 (163)
Error rate in %			
Non-switch trials	6.2 (3.6)	7.6 (4.3)	10.2 (5.1)
Switch trials	13.2 (7.8)	12.1 (5.9)	13.8 (6.7)

conducted to disentangle which of the single dependent variables contributed to the multivariate effect.

Transfer effects to RT measures

A three-factorial MANOVA for RT measures included near transfer mixing and switching costs, number switch mixing and switching costs, RT for correct trials on the 2-back task, Flanker interference score, and Stroop interference score, as well as simple and choice reaction time (see **Table 3** for mean performance on these dependent measures before and after training in the four different groups, and **Table A1** for complete mean RT data for switching and inhibition tasks). Analyses revealed a significant effect of time of measurement on the combined dependent variable of RT transfer measures, $F(9, 68) = 24.9$, Wilks' Lambda $= 0.23$, $p < 0.001$, partial $\eta^2 = 0.77$, indicating overall changes in RT measures from pretraining to posttraining assessments. Furthermore, there was a significant interaction term between time of measurement and cognitive training, $F(9, 68) = 2.7$, Wilks' Lambda $= 0.74$, $p < 0.009$, partial $\eta^2 = 0.26$, indicating that changes from pretraining to posttraining differed between groups with and without cognitive training. None of the other main or interaction effects reached significance. Therefore, follow-up analyses were conducted to explore the contribution of the individual RT measures for the effects of time and the interaction of time and cognitive training.

For RT mixing costs in the near transfer switching task (i.e., the food-size switching task), the separate ANOVA revealed a significant main effect of time, $F(1, 76) = 70.9$, $p < 0.001$, partial $\eta^2 = 0.48$, and a significant interaction term (Time × Cognitive Training), $F(1, 76) = 7.2$, $p < 0.009$, partial $\eta^2 = 0.09$. That is, the training groups reduced their RT mixing costs more from pre- to posttraining than the control groups – suggesting transfer to RT mixing costs in the near transfer switching task (see **Figure 2**). For switching costs in the near transfer task, analyses

Table 3 | Performance on main dependent RT measures in transfer tasks in the training groups (combined and cognitive training only) and control groups (exercise only and no-contact).

Training groups	Combined training		Cognitive training	
	Pretraining *M* (SD)	Posttraining *M* (SD)	Pretraining *M* (SD)	Posttraining *M* (SD)
Switching tasks				
Food/size MC (RT in ms)	213 (139)	97 (99)	206 (102)	64 (104)
Food/size SC (RT in ms)	221 (128)	137 (125)	242 (93)	114 (115)
Number MC (RT in ms)	727 (214)	537 (243)	724 (246)	560 (232)
Number SC (RT in ms)	199 (172)	81 (133)	121 (174)	123 (141)
Updating tasks				
2-back RT in ms	875 (118)	793 (111)	861 (97)	752 (130)
Inhibition tasks				
Flanker interference in ms	19 (26)	11 (25)	23 (28)	20 (38)
Stroop interference in s	18 (7)	15 (8)	19 (8)	18 (10)
Speed tasks				
Simple RT in ms	286 (42)	281 (39)	284 (57)	294 (63)
Choice RT in ms	440 (52)	426 (50)	441 (88)	415 (70)
Control groups	**Exercise only**		**No-contact**	
Switching tasks				
Food/size MC (RT in ms)	200 (109)	134 (107)	242 (124)	175 (75)
Food/size SC (RT in ms)	218 (125)	136 (85)	309 (157)	163 (136)
Number MC (RT in ms)	675 (325)	540 (211)	828 (217)	690 (173)
Number SC (RT in ms)	148 (140)	123 (175)	167 (201)	126 (144)
Updating tasks				
2-Back RT in ms	865 (109)	794 (99)	868 (101)	816 (106)
Inhibition tasks				
Flanker interference in ms	17 (41)	21 (26)	9 (20)	10 (33)
Stroop interference in s	17 (8)	13 (4)	18 (11)	15 (5)
Speed tasks				
Simple RT in ms	282 (36)	293 (36)	277 (30)	280 (37)
Choice RT in ms	439 (62)	439 (54)	428 (59)	426 (49)

MC, mixing costs; SC, switching costs; Flanker intereference (RT incongruent trials – RT congruent trials); Stroop interference (overall naming time 3rd run – overall naming time 2nd run).

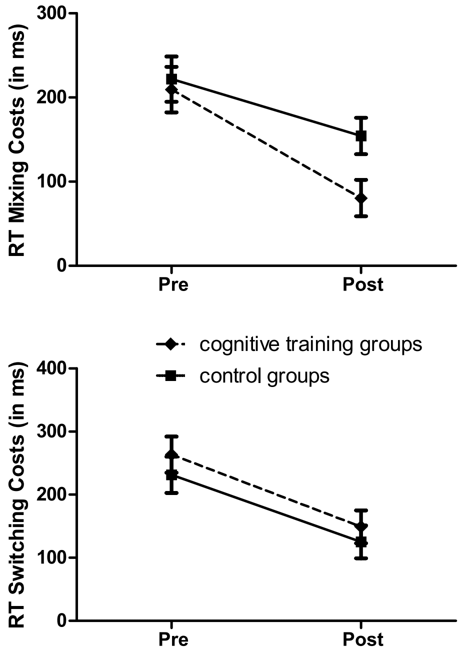

FIGURE 2 | Changes of RT mixing and switching costs (in ms ± SE) in near transfer switching task from pre- to posttraining assessments in the cognitive training groups and the control groups.

revealed a significant main effect of time for RT switching costs, $F(1, 76) = 72.5$, $p < 0.001$, partial $\eta^2 = 0.49$, indicating reductions of switching costs from pre- to posttest. The interaction term (Time × Cognitive Training) did not reach significance, indicating that training and control groups did not differ in their reduction of RT switching costs from pre- to posttest.

For the number switch task, analyses revealed a significant effect of time for RT mixing costs, $F(1, 76) = 53.7$, $p < 0.001$, partial $\eta^2 = 0.41$, and for RT switching costs, $F(1, 76) = 4.3$, $p < 0.04$, partial $\eta^2 = 0.05$. This indicates reductions of RT mixing and switching costs from pre- to posttest in all participants. The interaction term (Time × Cognitive Training) did not reach significance, indicating that training and control groups did not differ in their reduction of mixing or switching costs from pre- to posttest.

In the domain of updating, a significant effect of time was found for RT on correct responses in the 2-back task, $F(1, 76) = 67.7$, $p < 0.001$, partial $\eta^2 = 0.47$. This indicates that, overall, participants reacted faster posttraining than pretraining on the 2-back task. Importantly, there was a tendency for a significant interaction term (Time × Cognitive Training) for mean RT for correct responses, $F(1, 76) = 3.2$, $p < 0.08$, partial $\eta^2 = 0.04$, that is cognitive training groups tended to reduce their RTs more from pre- to posttest than control groups.

In the inhibition domain, no significant effects were found for the Flanker interference score, indicating neither changes from pre- to posttraining nor differences between cognitive training and control groups. For the Stroop interference score, analyses revealed a significant main effect of time, $F(1, 76) = 7.8$, $p < 0.006$, partial $\eta^2 = 0.09$, corresponding to reductions in the interference score from pretraining to posttraining. No other effects reached significance, indicating no differences between groups in changes from pre- to posttraining.

For mean choice reaction times, analyses revealed a significant main effect of time, $F(1, 76) = 7.1$, $p < 0.009$, partial $\eta^2 = 0.09$, that is participants performed the task faster at posttraining assessments than prior to training. Furthermore, there was a significant interaction term (Time × Cognitive Training) for mean choice reaction time, $F(1, 76) = 5.5$, $p < 0.02$, partial $\eta^2 = 0.07$, that is cognitive training groups reduced their RTs more from pre- to posttest than control groups. No significant effects were found for the simple reaction time task.

In summary, on the level of RT measures, transfer effects of a tasks switching training (as indicated by a significant interaction between time and cognitive training) were found. In particular, mixing costs in the near transfer task (switching) and choice reaction time (speed) contributed to this overall transfer effect. There was also a tendency for a contribution of the 2-back task (updating), but not for any of the other tasks included. Furthermore, on a RT level, there was no indication of an additional effect of the exercise intervention as would be indicated by a significant three-way interaction term between time, cognitive training, and exercise intervention.

Transfer effects to accuracy measures

A three-factorial MANOVA for accuracy measures included near transfer mixing and switching costs derived from error rates, number switch mixing and switching costs derived from error rates, accuracy rate (hits) for the 2-back task, accuracy rate in the keep track, the Flanker, and the choice reaction time task (see **Table 4** for mean performance on these measures before and after training in the four different groups **Table A2** for complete mean error data for switching tasks). Analyses revealed only one significant effect: the effect of cognitive training for the combined accuracy transfer measure, $F(8, 69) = 2.2$, Wilks' Lambda = 0.80, $p < 0.04$, partial $\eta^2 = 0.20$, indicating overall differences in accuracy measures for participants with and without cognitive training. No other main or interaction effects reached significance. Therefore, follow-up analyses were conducted to explore the contribution of the separate accuracy measures to the cognitive training effect.

On the accuracy level, analyses revealed no significant effect for switching costs in the near transfer tasks. For mixing costs on this tasks, analyses revealed a significant main effect of cognitive training group, $F(1, 76) = 7.2$, $p < 0.009$, partial $\eta^2 = 0.09$, indicating higher error rate mixing costs in the cognitive training groups compared to the control groups. For the number switch task, no significant effects were found for either switching or mixing costs derived from error rates. Neither in the updating domain (for accuracy in the 2-back task) nor in the inhibition domain (for accuracy in the Flanker task), significant effects were found, indicating no differences between cognitive training and control groups. For choice reaction accuracy rates there was a significant effect of cognitive training, $F(1, 76) = 5.9$, $p < 0.02$, partial $\eta^2 = 0.07$, with cognitive training groups having lower accuracy rates than control groups, overall.

To summarize, no transfer effect was found on the accuracy level for any of the tasks (as would be indicated by a significant interaction between time and cognitive training). Furthermore,

Table 4 | Performance on main dependent accuracy measures (in %) in transfer tasks in the training groups (combined and cognitive training only) and control groups (exercise only and no-contact).

Training groups	Combined training		Cognitive training	
	Pretraining *M* (SD)	Posttraining *M* (SD)	Pretraining *M* (SD)	Posttraining *M* (SD)
Switching tasks				
Food/size MC (error)	3.9 (4.2)	4.5 (5.7)	3.0 (5.2)	5.1 (8.6)
Food/size SC (error)	3.0 (5.1)	3.1 (7.1)	4.7 (4.6)	4.7 (7.4)
Number MC (error)	0.8 (11.3)	4.4 (8.9)	2.1 (6.5)	2.3 (6.4)
Number SC (error)	2.6 (5.7)	6.5 (8.7)	5.0 (9.4)	4.7 (9.2)
Updating tasks				
2-back accuracy (hits)	69.0 (11.2)	72.8 (16.2)	70.5 (11.1)	71.5 (12.4)
Keep track accuracy	59.8 (13.3)	63.8 (17.0)	62.5 (16.4)	67.4 (15.7)
Inhibition tasks				
Flanker accuracy	91.3 (10.8)	93.7 (4.4)	91.6 (6.1)	90.6 (7.2)
Stroop accuracy	99.3 (1.1)	99.8 (0.7)	99.4 (0.8)	99.7 (0.7)
Speed tasks				
Choice reaction accuracy	94.5 (4.5)	93.8 (4.3)	92.2 (5.8)	91.7 (7.7)
Control groups	**Exercise only**		**No-contact**	
Switching tasks				
Food/size MC (error)	1.6 (5.0)	1.3 (4.8)	1.5 (4.4)	2.6 (4.5)
Food/size SC (error)	4.6 (3.9)	1.9 (6.9)	3.4 (4.6)	3.4 (5.5)
Number MC (error)	2.6 (4.8)	3.8 (7.7)	2.9 (5.9)	−0.4 (10.8)
Number SC (error)	1.2 (6.5)	3.1 (7.6)	4.3 (7.5)	5.4 (6.1)
Updating tasks				
2-back accuracy (hits)	66.2 (13.5)	69.7 (15.9)	67.0 (17.2)	71.8 (15.4)
Keep track accuracy	62.2 (12.2)	63.6 (15.5)	63.1 (10.7)	64.2 (16.)
Inhibition tasks				
Flanker accuracy	89.4 (18.0)	93.7 (4.6)	93.6 (3.7)	92.2 (5.5)
Stroop accuracy	99.4 (0.7)	99.6 (0.8)	99.4 (1.0)	99.7 (0.6)
Speed tasks				
Choice reaction accuracy	95.4 (2.9)	95.8 (3.4)	94.9 (2.6)	95.0 (3.2)

MC, mixing costs; SC, switching costs.

there was no indication of an influence of the exercise intervention on the transfer effects on the accuracy level (as would be indicated by a significant three-way interaction term between time, cognitive training, and exercise intervention). Analyses indicated differences between groups with and without cognitive training. In particular, mixing costs (error) in the near transfer task and accuracy on the choice reaction time task contributed to this effect, with control participants performing better overall than trained participants.

RELATIONSHIPS BETWEEN TRAINING GAINS AND TRANSFER GAINS

To explore possible relationships between observed training gains and changes in performance in transfer tasks on the level of RTs, correlational analyses were conducted for the cognitive training groups. Training gains in RT switching costs (difference between first and last training day) were correlated with transfer gains (difference between pre- and posttraining assessment) in tasks where transfer effects had been indicated in the previous analyses, namely RT mixing costs in the near transfer switching task, choice reaction time, and RT for correct responses in the 2-back task. One significant correlation emerged between training gains in RT switching costs and pre-posttraining gains in RT in the 2-back task, $r = 0.42$, $p < 0.007$, indicating larger reductions of RT switching costs during training being associated with larger reductions in 2-back RT from pre- to posttraining in the trained groups.

DISCUSSION

Current study set out to explore if executive control can be trained in the age group of adolescents with a task switching training. Transfer was investigated systematically in all three executive control facets, i.e., switching, updating, and inhibition. Furthermore, current study aimed at exploring the recently proposed favorable effect of acute bouts of exercise on cognitive training. Analyses indicated that both training groups significantly reduced their switching costs (both on a RT and error rate level) over the course of three training sessions and also reduced their RT mixing costs in a near transfer task more from pre- to posttraining than the non-trained control groups. These findings indicate that executive control can be enhanced in adolescents through cognitive training. This is the first study to demonstrate plasticity of cognitive control in a group of adolescents and thus adds some novel findings to the growing literature on plasticity of executive control in different non-clinical age groups (Jaeggi et al., 2008; Karbach and Kray, 2009; Loosli et al., 2012). Interestingly, reductions of switching costs in this task switching training were found to be rather similar to those reported by Karbach and Kray (2009) for children and adults. This suggests a robust finding of significant reductions in switching costs over the course of very few (three or four, respectively) sessions of training with one session per week. A comparison of RTs over the course of training suggests that this training effect was driven by larger reductions in RTs in switch trials as compared to non-switch trials. This may indicate that training specifically improves processes necessary to switch from one task to the other as compared to a general speed up of responses. For error rates analyses indicated slight increases over training for non-switch trials whereas error rates in switch trials remained stable. Speculating on this finding, these changes in error rates may relate to slight reductions in motivation over training or increases in the relative focus on switch trials because of increased salience of the switching requirement.

Regarding transfer of the task switching training, current findings indicate some, but limited transfer of the training on the level of RT measures. First, transfer was found to a near transfer task, that was structurally similar to the one trained. Specifically, transfer was observed for RT mixing costs but not for RT switching costs. In contrast to the study by Karbach and Kray (2009), that found transfer for both types of costs in a near transfer switching task, our findings correspond to other studies that found transfer only to mixing costs (Minear and Shah, 2008). In Minear and Shah's and the current study transfer was found for the type of costs that corresponds to the more global ability to maintain and select two different task sets as opposed to switching costs that reflect more specifically the actual act of switching from one task to the other (Kray and Lindenberger, 2000; Braver et al., 2003). One may speculate that the specific task switching training used emphasizes the ability to maintain different tasks at the same time because there are no external cues and may therefore transfer reliably to other instances where maintenance is needed. During the task switching training, the participant has to maintain the tasks to be executed, keep track of how many times one task is executed, and keep track of which task to perform next. There is some evidence from other studies suggesting that updating or working memory (especially verbal rehearsal) is indeed crucial for performing these kinds of task switching tasks (Allen and Martin, 2010; Kray et al., 2010), especially if they are not cued trial-by-trial. The current study design does not allow to specifically investigate the changes of mixing costs during training. Because the training regimen by Karbach and Kray (2009) that we used in the current study does not include single-task blocks comparing performance between single and mixed tasks blocks (mixing costs) is not possible. Exploring changes of both types of performance costs over the course of training (that includes single-task blocks) and their relationship with transfer would therefore be an important avenue for future studies and would help to support our tentative suggestions about involved processes.

Improvements in the task switching training on a RT level were correlated with improvements in the speed of responses in an updating task. Furthermore, although not significant, a tendency for a transfer effect was found for the speed of responses in the updating task. This may support the importance of updating as a process possibly underlying the training and transfer effects in task switching trainings and may indicate that this particular (self-cued) task switching training improved the more general ability to update. This is in line with a recent study that demonstrated transfer of the same task switching training to a near transfer switching and an updating task that was associated with changes in right prefrontal and superior parietal brain regions as well as the striatum (Karbach and Brieber, 2011).

However, findings of transfer were generally rather limited as has also been suggested in other studies (e.g., Dowsett and Livesey, 2000; Li et al., 2008; Strobach et al., in press). In addition to transfer in one task switching and one updating task, transfer was found for a speed task on the RT measure (suggesting larger improvements in speed of simple decisions in the training as compared to the control groups), but neither for inhibition tasks nor to the other updating or switching tasks. Furthermore, in contrast to the RT measures, no indication of transfer was revealed on the level of accuracy in the transfer tasks. This may point to differential effects for speed- and accuracy-related measures. Findings may suggest that effects of a task switching training in adolescents manifest more in faster task execution (possibly related to faster updating and decision making) than in more accurate execution of tasks.

The transfer effects were not as strong as the ones reported by Karbach and Kray (2009) although the training regimen were very similar. Different possible factors may explain this discrepancy. Firstly, it may be that one modification we did to their protocol in terms of duration (three versus four sessions) has resulted in a training dose that was not enough to produce robust transfer effects. That is a possibility, especially when comparing current training regimen with considerably more extensive training regimen like the ones used by Jaeggi et al. (2008, with 8–19 sessions) or Klingberg et al. (2005, with 25 sessions) and recent study that even included as many as 100 training sessions (Schmiedek et al., 2010). However, Karbach and Kray (2009) found a range of transfer effects with only four training sessions. In addition, more importantly, training improvements in the current study were comparable to those reported by Karbach and Kray (2009). Nevertheless, it is reasonable to assume that a certain amount or intensity of executive control training may be a prerequisite for substantial changes to occur (see, e.g., Klingberg, 2010) and we would find broader transfer effects with a larger amount of training. Considering plasticity as the potential of brain and behavior to change in response to environmental challenges (e.g., cognitive demands of an executive control training), the amount of plastic changes, and therefore the amount of transfer may strongly depend on the intensity and duration of the challenge. Spacing of the cognitive training sessions may also play a role here, that is, whether training sessions are concentrated over a short period of time (e.g., daily sessions like in the study by Jaeggi et al., 2008) or spaced over several weeks like in the current study.

Furthermore, the target age group of the current study may be of relevance for the observed lower amounts of transfer. It may be that in the group of adolescents, although there are still mean level changes observable in normative developmental studies, domains of executive control may show different developmental trajectories (Huizinga et al., 2006) and may therefore be more or less prone to training and transfer effects than in other age groups. It is also possible that the specific transfer tasks used did not share enough relevant features or required processes with the trained task to find reliable transfer. For example, it could be that task switching training enhanced aspects of maintenance ability and transfer to the number switch task was not found because task choice was cued and requirements to maintain task order and number were very low in this transfer task (the cue was present the whole time until a response was made, thus very little maintenance is needed). Thus, future studies on the plasticity of executive control functions should explore the moderating effects of training domain and training intensity, as well as the role of age-dependent differences on the effects of cognitive trainings (Klingberg, 2010).

The third exploratory research question concerned a novel proposal in the training literature (e.g., Hillman et al., 2009), i.e., possible effects of a combination of an acute exercise intervention with the cognitive training. Analyses revealed no reliable effects of this intervention on training or transfer tasks. Thus, our initial data does not provide strong evidence in favor of the suggestion that this type of exercise intervention may have a positive impact on the effects of cognitive training. However, of course, our findings are preliminary and could be due to different factors. It could be that, in this context, acute exercise has no effect on task switching and/or learning. This is in accordance with studies that have not been able to show an effect of acute exercise on switching (e.g., Tomporowski et al., 2008, but, see, e.g., Pesce et al., 2003 for findings of positive effects). Other domains of cognitive control may be more receptive for these kinds of effects, e.g., there are a range of studies showing improvements in inhibition tasks (e.g., Hillman et al., 2009; Yanagisawa et al., 2010, but, see, e.g., Stroth et al., 2009 for findings of no such effect). It is also possible that different intensities or types of exercise would have different effects, for example exercise that requires more coordination skills than cycling as has been suggested in a study by Budde et al. (2008). In addition, it is important to note from a methodological point of view that most studies on acute exercise effects used a within-subjects design (see, e.g., Pontifex et al., 2009; Stroth et al., 2009; Yanagisawa et al., 2010) whereas current study employed a between-subjects design to compare exercise to non-exercise. That may have made it more difficult to detect possibly small effects. To further explore the proposed effects of exercise, future research will have to further examine these issues by exploring the effects of different types of exercise on cognitive training efficiency.

To summarize, current study showed that task switching abilities can be trained in adolescents. Transfer was revealed at the level of RT measures in a similar task switching task, a speed task and a (tendency for) an updating task. Conceptually interesting, updating seems to play a crucial role in this task switching training and its possible transfer effects. The importance of updating processes is in line with a range of cognitive training studies that have used updating and working memory tasks and have been able to show robust training and transfer effects. An additional positive effect of acute exercise could not be demonstrated – thus, possible factors that influence the amount of training and transfer effects remain to be explored in future studies.

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REFERENCES

Allen, C. M., and Martin, R. C. (2010). Role of phonological short-term memory in global but not local task switch costs. *Abstr. Psychon. Soc.* 15, 91.

Anderson, P. (2002). Assessment and development of executive function (EF) during childhood. *Child Neuropsychol.* 8, 71–82.

Baddeley, A. D. (2003). Working memory: looking back and looking forward. *Nat. Rev. Neurosci.* 4, 829–839.

Berryhill, M. E., and Hughes, H. C. (2009). On the minimization of task switch costs following long-term training. *Atten. Percept. Psychophys.* 71, 503–514.

Bherer, L., Kramer, A. F., Peterson, M. S., Colcombe, S., Erickson, K., and Becic, E. (2005). Training effects on dual-task performance: are there age-related differences in plasticity of attentional control? *Psychol. Aging* 20, 695–709.

Bös, K., Worth, A., Opper, E., Oberger, J., and Woll, A. (2009). *Motorik-Modul: Eine Studie zur motorischen Leistungsfähigkeit und körperlich-sportlichen Aktivität von Kindern und Jugendlichen in Deutschland.* Baden-Baden: Nomos Verlag.

Braver, T. S., Reynolds, J. R., and Donaldson, D. I. (2003). Neural mechanisms of transient and sustained cognitive control during task switching. *Neuron* 39, 713–726.

Buchler, N. G., Hoyer, W. J., and Cerella, J. (2008). Rules and more rules: the effects of multiple tasks, extensive training, and aging on task-switching performance. *Mem. Cognit.* 36, 735–748.

Budde, H., Voelcker-Rehage, C., Pietraßyk-Kendziorra, S., Ribeiro, P., and Tidow, G. (2008). Acute coordinative exercise improves attentional performance in adolescents. *Neurosci. Lett.* 441, 219–223.

Bunge, S. A., Dudukovic, N. M., Thomason, M. E., Vaidya, C. J., and Gabrieli, J. D. E. (2002). Immature frontal lobe contributions to cognitive control in children: evidence from fMRI. *Neuron* 33, 301–311.

Buschkuehl, M., Jaeggi, S. M., Hutchison, S., Perrig-Chiello, P., Däpp, C., Müller, M., Breil, F., Hoppeler, H., and Perrig, W. J. (2008). Impact of working memory training on memory performance in old-old adults. *Psychol. Aging* 23, 743–753.

Cepeda, N. J., Kramer, A. F., and de Sather, J. C. G. (2001). Changes in executive control across the life span: examination of task-switching performance. *Dev. Psychol.* 37, 715–730.

Dahlin, E., Nyberg, L., Bäckman, L., and Neely, A. S. (2008). Plasticity of executive functioning in young and older adults: immediate training gains, transfer, and long-term maintenance. *Psychol. Aging* 23, 720–730.

Davidson, M. C., Amso, D., Anderson, L. C., and Diamond, A. (2006). Development of cognitive control and executive functions from 4 to 13 years: evidence from manipulations of memory, inhibition, and task switching. *Neuropsychologia* 44, 2037–2078.

Dietrich, A. (2006). Transient hypofrontality as a mechanism for the psychological effects of exercise. *Psychiatry Res.* 145, 79–83.

Dietrich, A., and Sparling, P. B. (2004). Endurance exercise selectively impairs prefrontal-dependent cognition. *Brain Cogn.* 55, 516–524.

Dowsett, S. M., and Livesey, D. J. (2000). The development of inhibitory control in preschool children: effects of "executive skills" training. *Dev. Psychobiol.* 36, 161–174.

Ellemberg, D., and St-Louis-Deschênes, M. (2010). The effect of acute physical exercise on cognitive function during development. *Psychol. Sport Exerc.* 11, 122–126.

Engle, R. W., Tuholski, S. W., Laughlin, J. E., and Conway, A. R. (1999). Working memory, short-term memory, and general fluid intelligence: a latent-variable approach. *J. Exp. Psychol. Gen.* 128, 309–331.

Eriksen, B. A., and Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a non-search task. *Percept. Psychophys.* 16, 143–149.

Hillman, C. H., Pontifex, M. B., Raine, L. B., Castelli, D. M., Hall, E. E., and Kramer, A. F. (2009). The effect of acute treadmill walking on cognitive control and academic achievement in preadolescent children. *Neuroscience* 159, 1044–1054.

Hogervorst, E., Riedel, W., Jeukendrup, A., and Jolles, J. (1996). Cognitive performance after strenuous physical exercise. *Percept. Mot. Skills* 83, 479–488.

Holmes, J., Gathercole, S. E., and Dunning, D. L. (2009). Adaptive training leads to sustained enhancement of poor working memory in children. *Dev. Sci.* 12, F9–F15.

Huizinga, M., Dolan, C. V., and van der Molen, M. W. (2006). Age-related change in executive function: developmental trends and a latent variable analysis. *Neuropsychologia* 44, 2017–2036.

Jaeggi, S. M., Buschkuehl, M., Jonides, J., and Perrig, W. J. (2008). Improving fluid intelligence with training on working memory. *Proc. Natl. Acad. Sci. U.S.A.* 105, 6829–6833.

Jaeggi, S. M., Buschkuehl, M., Jonides, J., and Shah, P. (2011). Short- and long-term benefits of cognitive training. *Proc. Natl. Acad. Sci. U.S.A.* 108, 10081–10086.

Karbach, J., and Brieber, S. (2011). Neural correlates of executive control training. *Talk Presented at the 12th Meeting of the European Society for Cognitive Psychology.* San Sebastian.

Karbach, J., and Kray, J. (2009). How useful is executive control training? Age differences in near and far transfer of task-switching training. *Dev. Sci.* 12, 978–990.

Klingberg, T. (2010). Training and plasticity of working memory. *Trends Cogn. Sci. (Regul. Ed.)* 14, 317–324.

Klingberg, T., Fernell, E., Olesen, P. J., Johnson, M., Gustafsson, P., Dahlstrom, K., Gillberg, C. G., Forssberg, H., and Westerberg, H. (2005). Computerized training of working memory in children with ADHD – a randomized, controlled trial. *J. Am. Acad. Child Adolesc. Psychiatry* 44, 177–186.

Koch, I., and Allport, A. (2006). Cue-based preparation and stimulus-based priming of tasks in task switching. *Mem. Cognit.* 34, 433–444.

Kramer, A. F., Hahn, S., and Gopher, D. (1999). Task coordination and aging: explorations of executive control processes in the task switching paradigm. *Acta Psychol. (Amst.)* 101, 339–378.

Kray, J., Eber, J., and Karbach, J. (2008). Verbal self-instructions in task switching: a compensatory tool for action-control deficits in childhood and old age? *Dev. Sci.* 11, 223–236.

Kray, J., and Lindenberger, U. (2000). Adult age differences in task switching. *Psychol. Aging* 15, 126–147.

Kray, J., Lucenet, J., and Blaye, A. (2010). Can older adults enhance task-switching performance by verbal self-instructions? The influence of working-memory load and early learning. *Front. Aging Neurosci.* 2:147. doi:10.3389/fnagi.2010.00147

Lambourne, K., and Tomporowski, P. (2010). The effect of exercise-induced arousal on cognitive task performance: a meta-regression analysis. *Brain Res.* 1341, 12–24.

Lehto, J. E., Juujärvi, P., Kooistra, L., and Pulkkinen, L. (2003). Dimensions of executive functioning: evidence from children. *Br. J. Dev. Psychol.* 21, 59–80.

Li, S.-C., Schmiedek, F., Huxhold, O., Röcke, C., Smith, J., and Lindenberger, U. (2008). Working memory plasticity in old age: practice gain, transfer, and maintenance. *Psychol. Aging* 23, 731–742.

Liepelt, R., Strobach, T., Frensch, P., and Schubert, T. (2011). Improved intertask coordination after extensive dual-task practice. *Q. J. Exp. Psychol.* 64, 1251–1272.

Loosli, S. V., Buschkuehl, M., Perrig, W. J., and Jaeggi, S. M. (2012). Working memory training improves reading processes in typically developing children. *Child Neuropsychol.* 18, 62–78.

Luna, B., Garver, K. E., Urban, T. A., Lazar, N. A., and Sweeney, J. A. (2004). Maturation of cognitive processes from late childhood to adulthood. *Child Dev.* 75, 1357–1372.

Luna, B., Padmanabhan, A., and O'Hearn, K. (2010). What has fMRI told us about the development of cognitive control through adolescence? *Brain Cogn.* 72, 101–113.

Magnié, M. N., Bermon, S., Martin, F., Madany-Lounis, M., Suisse, G., Muhammad, W., and Dolisi, C. (2000). P300, N400, aerobic fitness, and maximal aerobic exercise. *Psychophysiology* 37, 369–377.

Mayr, U. (2003). "Towards principles of executive control: how mental sets are selected," in *Principles of Learning and Memory*, eds R. H. Kluwe, G. Lüer, and F. Rösler (Berlin: Birkhäuser), 223–240.

McDaniel, M., and Bugg, J. (in press). Memory training interventions: what has been forgotten? *J. Appl. Res. Mem. Cogn.*

Minear, M., and Shah, P. (2008). Training and transfer effects in task switching. *Mem. Cognit.* 36, 1470–1483.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., and Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "Frontal Lobe" tasks: a latent variable analysis. *Cogn. Psychol.* 41, 49–100.

Norman, W., and Shallice, T. (1986). "Attention to action," in *Consciousness and Self Regulation: Advances in Research and Theory*, Vol. 4, eds R. J. Davidson, G. E. Schwartz, and D. Shapiro (New York: Plenum), 1–18.

Olesen, P. J., Westerberg, H., and Klingberg, T. (2004). Increased prefrontal and parietal activity after training of working memory. *Nat. Neurosci.* 7, 75–79.

Oswald, W. D., and Fleischmann, U. M. (1995). *Nürnberger-Alters-Inventar (NAI). NAI-Testmanual und -Textband.* Göttingen: Hogrefe.

Pesce, C., Capranica, L., Tessitore, A., and Figura, F. (2003). Focusing of visual attention under submaximal physical load. *Int. J. Sport Exerc. Psychol.* 1, 275–292.

Pesce, C., Crova, C., Cereatti, L., Casella, R., and Bellucci, M. (2009). Physical activity and mental performance in preadolescents: effects of acute exercise on free-recall memory. *Ment. Health Phys. Act.* 2, 16–22.

Petermann, F., and Petermann, U. (2010). *HAWIK-IV*. Bern: Huber.

Pontifex, M. B., Hillman, C. H., Fernhall, B., Thompson, K. M., and Valentini, T. A. (2009). The effect of acute aerobic and resistance exercise on working memory. *Med. Sci. Sports Exerc.* 41, 927–934.

Rubia, K., Smith, A. B., Woolley, J., Nosarti, C., Heyman, I., Taylor, E., and Brammer, M. (2006). Progressive increase of frontostriatal brain activation from childhood to adulthood during event-related tasks of cognitive control. *Hum. Brain Mapp.* 27, 973–993.

Schmiedek, F., Lövdén, M., and Lindenberger, U. (2010). Hundred days of cognitive training enhance broad cognitive abilities in adulthood: findings from the COGITO study. *Front. Aging Neurosci.* 2:27. doi:10.3389/fnagi.2010.00027

Snodgrass, J., and Vanderwart, M. (1980). A standardized set of 260 pictures: norms for name agreement, image agreement, familiarity, and visual complexity. *J. Exp. Psychol. Hum. Learn.* 6, 174–215.

Strobach, T., Frensch, P. A., Soutschek, A., and Schubert, T. (in press). Investigation on the improvement and transfer of dual-task coordination skills. *Psychol. Res.*

Strobach, T., Liepelt, R., Schubert, T., and Kiesel, A. (2012). Task switching: effects of practice on switch and mixing costs. *Psychol. Res.* 76, 74–83.

Stroth, S., Kubesch, S., Dieterle, K., Ruchsow, M., Heim, R., and Kiefer, M. (2009). Physical fitness, but not acute exercise modulates event-related potential indices for executive control in healthy adolescents. *Brain Res.* 1269, 114–124.

Themanson, J. R., and Hillman, C. H. (2006). Cardiorespiratory fitness and acute aerobic exercise effects on neuroelectric and behavioral measures of action monitoring. *Neuroscience* 141, 757–767.

Thorell, L. B., Lindqvist, S., Nutley, S. B., Bohlin, G., and Klingberg, T. (2009). Training and transfer effects of executive functions in preschool children. *Dev. Sci.* 12, 106–113.

Tomporowski, P. D. (2003). Effects of acute bouts of exercise on cognition. *Acta Psychol. (Amst.)* 112, 297–324.

Tomporowski, P. D., Davis, C. L., Lambourne, K., Gregoski, M., and Tkacz, J. (2008). Task switching in overweight children: effects of acute exercise and age. *J. Sport Exerc. Psychol.* 30, 497–511.

van der Sluis, S., de Jong, P. F., and van der Leij, A. (2007). Executive functioning in children, and its relations with reasoning, reading, and arithmetic. *Intelligence* 35, 427–449.

Yanagisawa, H., Dan, I., Tsuzuki, D., Kato, M., Okamoto, M., Kyutoku, Y., and Soya, H. (2010). Acute moderate exercise elicits increased dorsolateral prefrontal activation and improves cognitive performance with Stroop test. *Neuroimage* 50, 1702–1710.

Zinke, K., Zeintl, M., Eschen, A., Herzog, C., and Kliegel, M. (2012). Potentials and limits of plasticity induced by working memory training in old-old age. *Gerontology* 58, 79–87.

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APPENDIX

Table A1 | Mean RT data for transfer task switching and inhibition tasks in the training groups (combined and cognitive training only) and control groups (exercise only and no-contact).

Training groups	**Combined training**		**Cognitive training**	
	Pretraining *M* (SD)	**Posttraining *M* (SD)**	**Pretraining *M* (SD)**	**Posttraining *M* (SD)**
Food/size switching task (mean RT in ms)				
Single trials	684 (109)	611 (100)	686 (171)	612 (180)
Non-switch trials	789 (166)	642 (103)	774 (188)	621 (180)
Switch trials	1010 (263)	778 (180)	1016 (252)	735 (260)
Number switching task (mean RT in ms)				
Single trials	656 (85)	636 (104)	661 (118)	633 (171)
Non-switch trials	1285 (246)	1135 (223)	1329 (293)	1135 (314)
Switch trials	1484 (276)	1216 (280)	1450 (364)	1258 (313)
Flanker inhibition task (mean RT in ms)				
Congruent trials	554 (60)	507 (59)	559 (99)	515 (100)
Incongruent trials	573 (58)	518 (65)	582 (104)	535 (93)
Stroop inhibition task (overall time in s)				
Second run (color patches)	26 (7)	24 (5)	25 (5)	24 (5)
Third run (color names)	44 (10)	39 (12)	44 (10)	42 (11)
Control groups	**Exercise only**		**No-contact**	
Food/size switching task (mean RT in ms)				
Single trials	691 (133)	641 (123)	726 (147)	650 (117)
Non-switch trials	783 (186)	707 (169)	816 (175)	745 (138)
Switch trials	1002 (273)	843 (225)	1125 (301)	908 (189)
Number switching task (mean RT in ms)				
Single trials	678 (132)	659 (111)	671 (92)	621 (87)
Non-switch trials	1279 (367)	1147 (266)	1420 (277)	1244 (183)
Switch trials	1427 (450)	1269 (326)	1586 (257)	1371 (245)
Flanker inhibition task (mean RT in ms)				
Congruent trials	559 (87)	537 (63)	539 (64)	523 (79)
Incongruent trials	575 (96)	558 (71)	548 (63)	532 (70)
Stroop inhibition task (overall time in s)				
Second run (color patches)	26 (5)	26 (6)	27 (6)	26 (6)
Third run (color names)	43 (11)	38 (6)	45 (16)	41 (9)

Table A2 | Mean error data for transfer task switching tasks in the training groups (combined and cognitive training only) and control groups (exercise only and no-contact).

Training groups	**Combined training**		**Cognitive training**	
	Pretraining *M* (SD)	**Posttraining *M* (SD)**	**Pretraining *M* (SD)**	**Posttraining *M* (SD)**
Food/size switching task (mean error rate in %)				
Single trials	8.2 (5.0)	13.2 (10.3)	8.9 (6.2)	16.4 (10.0)
Non-switch trials	10.5 (6.7)	16.1 (12.1)	9.5 (6.3)	19.2 (14.4)
Switch trials	13.6 (8.0)	19.1 (12.7)	14.2 (7.5)	23.9 (12.5)
Number switching task (mean error rate in %)				
Single trials	9.3 (11.2)	8.8 (4.4)	8.4 (7.0)	11.6 (7.2)
Non-switch trials	10.3 (8.1)	11.4 (11.4)	11.3 (13.2)	12.4 (9.0)
Switch trials	12.9 (7.2)	17.9 (13.2)	16.3 (11.9)	17.1 (11.6)
Control groups	**Exercise only**		**No-contact**	
Food/size switching task (mean error rate in %)				
Single trials	7.4 (4.2)	8.5 (5.7)	6.4 (4.2)	8.4 (6.3)
Non-switch trials	6.7 (4.1)	8.9 (5.9)	6.3 (4.0)	9.3 (6.4)
Switch trials	11.3 (5.7)	10.8 (8.9)	9.7 (5.7)	12.7 (6.2)
Number switching task (mean error rate in %)				
Single trials	7.5 (10.1)	7.9 (6.2)	5.7 (4.6)	10.1 (9.4)
Non-switch trials	10.5 (10.7)	11.2 (11.5)	7.9 (5.3)	7.1 (5.3)
Switch trials	11.7 (10.7)	14.4 (12.6)	12.2 (8.0)	12.6 (7.7)

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A combined robotic and cognitive training for locomotor rehabilitation: evidences of cerebral functional reorganization in two chronic traumatic brain injured patients

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It has been demonstrated that automated locomotor training can improve walking capabilities in spinal cord-injured subjects but its effectiveness on brain damaged patients has not been well established. A possible explanation of the discordant results on the efficacy of robotic training in patients with cerebral lesions could be that these patients, besides stimulation of physiological motor patterns through passive leg movements, also need to train the cognitive aspects of motor control. Indeed, another way to stimulate cerebral motor areas in paretic patients is to use the cognitive function of motor imagery. A promising possibility is thus to combine sensorimotor training with the use of motor imagery. The aim of this paper is to assess changes in brain activations after a combined sensorimotor and cognitive training for gait rehabilitation. The protocol consisted of the integrated use of a robotic gait orthosis prototype with locomotor imagery tasks. Assessment was conducted on two patients with chronic traumatic brain injury and major gait impairments, using functional magnetic resonance imaging. Physiatric functional scales were used to assess clinical outcomes. Results showed greater activation post-training in the sensorimotor and supplementary motor cortices, as well as enhanced functional connectivity within the motor network. Improvements in balance and, to a lesser extent, in gait outcomes were also found.

Keywords: motor training, cognitive training, motor imagery, locomotor rehabilitation, brain injury, robotic gait orthosis, functional magnetic resonance imaging, brain plasticity

INTRODUCTION

Patients with severe traumatic brain injury (TBI) may develop seriously disabling motor disorders, which may be due to lesions of the corticospinal pathways, and extrapyramidal as well as multisensory dysfunction. Deconditioning also decreases somatosensory input and disrupts body image. Rehabilitation exercises that stimulate the remaining, intact central nervous system are based on the assumption that the brain partly makes up for lost functions, through neuroplasticity. During the learning of new skills, cortical regions associated with sensorimotor function of the body parts most utilized for the skilled task gradually start to be represented over larger cortical territories (Pascual-Leone et al., 1994; Karni et al., 1995). Besides, some studies have shown that functional and structural changes take place in the cerebral cortex after injury (for a review, see Rossini et al., 2007). These two modulators of cerebral function, behavioral experience and brain injury, interact. Hence it is likely that after traumatic brain injuries, the sensorimotor experiences of the individual can remodel the structure and function of undamaged parts of the brain, thus promoting recovery.

The most recent technique for gait rehabilitation makes use of robotic systems that move the patient's legs in a physiological way on a moving treadmill, while a body weight support (BWS) system with its harness supports the patient's weight. It has been demonstrated that automated locomotor training can improve walking capabilities in spinal cord-injured subjects (Colombo et al., 2000, 2001; Jezernik et al., 2003; Wirz et al., 2005), but its effectiveness on brain damaged patients – i.e., stroke and TBI patients – has not been well established. Indeed, while some studies on stroke patients found better outcomes when robotic rather than conventional training is used (e.g., Mayr et al., 2007; Schwartz et al., 2009), other studies (e.g., Husemann et al., 2007; Westlake and Patten, 2009) obtained intermediate results (found no significant differences in primary outcomes between conventional and robotic therapy, but more improvements on secondary outcomes in the robotic-assisted group), and some others even found the opposite result, i.e., superior effectiveness for the conventional training (e.g., Hornby et al., 2008; Hidler et al., 2009), and thus cast doubts on the validity of robotic- vs. therapist-assisted locomotor training in chronic post-stroke patients. A Cochrane review (Mehrholz et al., 2007) on 414 stroke patients showed that robotic training in combination with physiotherapy improves some gait parameters, but not others; it also suggests caution in interpreting the results, because protocols and patient status vary greatly across studies and some trials tested electromechanical devices in combination with functional electrical stimulation. Finally, as far as TBI patients are concerned, we found no study employing robotic gait rehabilitation (RGR) protocols. A possible explanation of the above mentioned discordant results on the efficacy of robotic training in patients with cerebral lesions could be that these patients, besides stimulation of physiological motor patterns through passive leg movements, also need to train the cognitive aspects of motor control. Indeed, another way to stimulate cerebral motor areas in paretic patients is to use the cognitive function of motor imagery, which implies that the subject forms a representation of a given motor act: during kinesthetic motor imagery the subject is asked to imagine the introspective sensorimotor feeling of moving the limb. There are evidences that brain injured patients retain the ability to generate accurate motor images of actions they cannot perform (Decety and Boisson, 1990; Sirigu et al., 1995), and that mental practice of motor skills can improve actual performance (Jackson et al., 2001). Thus, motor imagery can be considered a potentially effective intervention in the rehabilitation of patients with motor impairments. However, the efficacy of this technique could be limited by the fact that imagery does not provide somatosensory afferents, which constitute the main intrinsic feedback in relearning movements. A promising possibility is thus to combine sensorimotor training with the use of motor imagery (Jackson et al., 2004; Malouin et al., 2004).

A combined robotic and cognitive protocol for locomotor rehabilitation had not been developed so far. We therefore designed a robotic and cognitive gait rehabilitation (RCGR) protocol, whose strength lies in the integrated use of both sensorimotor and cognitive stimulations. Sensorimotor training is provided thanks to a pneumatic active gait orthosis that we designed and built (Belforte et al., 1997, 2001), which induces lower limb movements. The robotic orthosis design and its characteristics are briefly described in this paper. Cognitive training consists of a series of locomotor imagery tasks to be performed both during and immediately after the robotic-assisted session. The proprioceptive and kinesthetic activation induced by the passive leg movements provides reproducible and constant afferent input to the motor control centers, facilitating central pattern generators and enhancing motor drive; also, such proprioceptive sensations are essential for the parallel cognitive training. Indeed, it is very difficult to imagine a procedural action such as that of walking, as it normally does not require any conscious attention. Thus, the proprioceptive inputs received during the passive training are the only help the patient has when mentally representing a motor sequence of locomotion. On the other hand, the mental imagery employed during the robotic-assisted motion focuses the patient's conscious attention on the ongoing steps: as walking in normal subjects is an automated – mainly subcortical – activity, focusing the patient's conscious attention on the movements involved in ambulation is crucial in order to make him/her reacquire motor representations.

The goal of this paper is to evaluate the brain changes following our RCGR protocol by evaluating possible cerebral functional reorganizations. To this end, we submitted two clinical cases (chronic paretic patients with TBI) to our RCGR protocol and assessed their cerebral changes using functional magnetic resonance imaging (fMRI), an *in vivo* imaging technique which allows the mapping of active processes within the brain. fMRI has been previously used to study training-induced plasticity in stroke patients (for a review see Nelles, 2004); locomotor training-related brain changes have been recently investigated in children with cerebral lesions (de Bode et al., 2007; Phillips et al., 2007), but similar data for adult patients is still lacking. To the best of our knowledge, there are no fMRI studies assessing RGR in adult brain injured patients.

The fMRI assessments were aimed at investigating whether the RCGR rehabilitation led to changes in cerebral activations. Our predictions are based on the results of previous work we carried out on healthy subjects (Sacco et al., 2006, 2009): we found that combined locomotor and cognitive training modifies sensorimotor activation of the brain, leading to greater activation of the premotor and supplementary motor areas (SMA), the primary motor and somatosensory areas of the dominant hemisphere, as well as an increasing functional connectivity within the motor network. A manifestation of functional connectivity is the covariance of metabolic rates in functionally related brain regions (Friston et al., 1993): coherent changes in blood flow imply neuronal connections. Thus, in line with our previous results, we hypothesized that the RCGR training can enhance both sensorimotor activations in the cortical areas involved in lower limb representation, and functional connectivity, i.e., interconnections between brain regions.

MATERIALS AND METHODS

THE ROBOTIC GAIT ORTHOSIS

In the last decade, many robotic devices for lower limb rehabilitations have been developed (for a recent review see Waldner et al., 2009). The robotic gait orthosis we used is a prototype developed by our group for TBI gait rehabilitation purposes (differences from the existing devices are described below). It consists of a modified reciprocating gait orthosis (RGO) integrated with a pneumatic actuation system for knee and hip joints. Hinges that enable rotation in the sagittal plane replace the RGO's original locked joints. The hip angle ranges from −20° flexion to 20° extension and the knee angle from 0° extension to 90° flexion. Joint actuation is provided by double acting pneumatic cylinders that are positioned on the passive RGO structure and controlled by a PLC (Programmable Logic Controller) and a group of electrovalves. See **Figure 1**.

For the hip actuation (**Figure 2A**), a cylindrical tube is fixed to the rear RGO tube, whereas the rod is hinged on a metal plate that is integral with the femoral segment of the orthosis. A cable connects the two hips and makes their movement reciprocal, that is the extension of one hip achieves flexion in the opposite hip. This enables a crossed hip joint actuation strategy and a simple

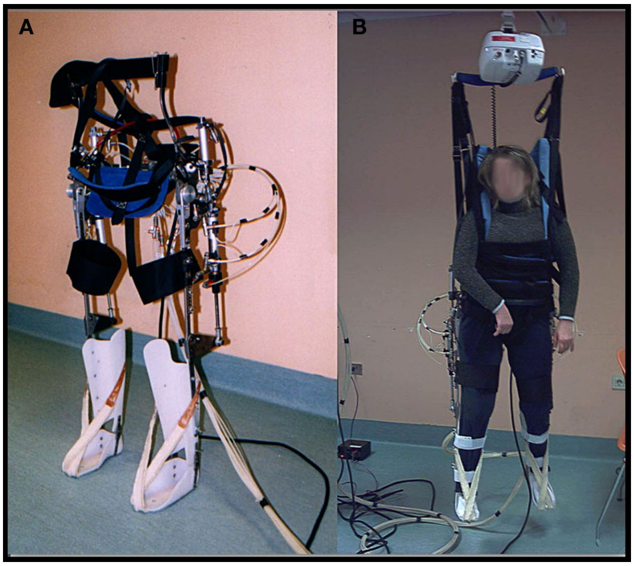

FIGURE 1 | Active RGO used for training, alone (A) and worn by subject (B).

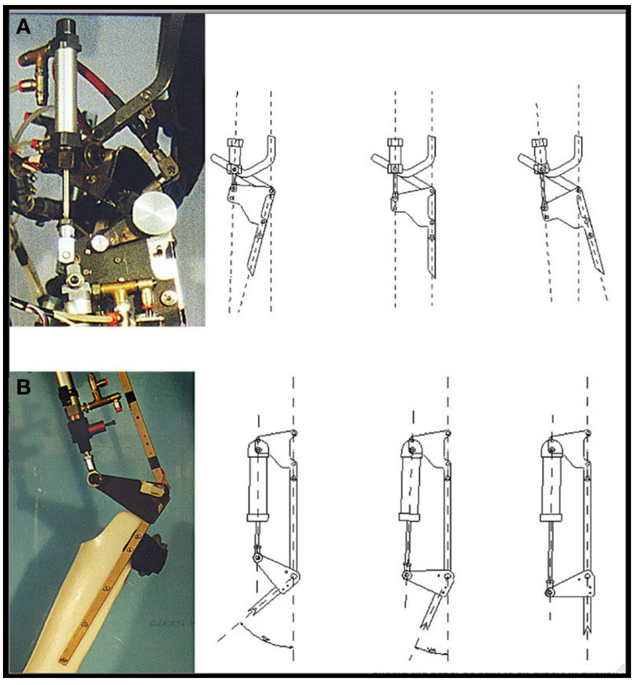

FIGURE 2 | Details of hip (A) and knee (B) actuation system. (Source, Li et al., 2008).

control of the neutral trunk position with respect to the legs. Knee actuation (**Figure 2B**) is based on the same principle: a double acting pneumatic cylinder has its tube fixed to the orthosis's femoral segment whereas its rod is hinged on a metal plate that is integral with the tibial segment. The suitably positioned hinge helps create the necessary lever arm action to generate appropriate torque on the joint. The ankle joint is passive: the foot and calf are fixed to an ankle foot orthosis (AFO) and elastic elements keep the foot in slight dorsiflexion so to prevent it dropping. The robotic orthosis is able to reproduce a gait cycle according to two different modes: *step-by-step* or *continuous*. Step-by-step mode requires user consent after each step in order to proceed to the following step, whereas in the continuous mode the orthosis imposes the gait cycle according to established parameters.

The robotic orthosis is used together with a BWS system, as in most rehabilitation protocols, while, unlike other devices, it does not make use of a treadmill. This choice has been made to allow the patient actually to move forward, according to the kinematic settings. This system should offer a more physiological context for gait rehabilitation, avoiding the proprioceptive, visual, and vestibular mismatch generated by walking on the spot on a treadmill. Moreover, patients with TBI often exhibit not only pyramidal motor impairment but also major balance and coordination disorders, owing to multi-level cerebellar, vestibular, and sensorial damage, thus generating additional difficulties in carrying out functional dynamic tasks (Basford et al., 2003). A more physiological sensorimotor task would also enable more coherent perception (Berthoz, 2000), enhancing memory of movement and facilitating motor imagery sessions. Finally, a gait system not bound to a treadmill allows training in different kinds of environments, such as slopes, steps, etc., without requiring large spaces or structured environments: a room with a ceiling guide for simple BWS is sufficient.

Our robotic system, unlike the existing devices, uses a pneumatic as opposed to an electric actuation system. This choice has been made primarily because compressed air is very compliant and thus helps in avoiding clasp-knife rigidity, i.e., a sudden increase in tone when antigravity muscles are contracted. Indeed, this phenomenon, which is due to spasticity and thus very frequent in brain injured patients, abnormally increases resistance on passive stretching and interferes with both extension and flexion. Also, compressed air is intrinsically safe, clean, and usually easily available in most medical centers.

PATIENTS AND REHABILITATION PROTOCOL

The protocol was approved by the local Ethics Committee (Department of Psychology, University of Turin, Italy). Two chronic traumatic brain injured patients were recruited from the "Centro Puzzle" in Turin. The patients gave their written informed consent for both the rehabilitation protocol and the fMRI scanning. The inclusion criteria required an observable walking deficit, active ankle dorsi- and plantarflexion, and no observable motor recovery in the previous 12 months in spite of standard rehabilitation programs. The exclusion criteria comprised the presence of lower limb peripheral neuropathies, spinal lesions, previous pathologies of the central nervous system, cognitive deterioration (MMSE <24), aphasia, psychiatric illness or severe behavioral alterations, drug or alcohol abuse, severe visual or auditory deficits, severe orthopedic impairments, and magnetic resonance incompatible intra-body devices.

Patient S.R., was a 28-year-old male, right-handed and right-footed, with TBI that had occurred 5 years earlier, with diffuse axonal damage and major gait impairment owing to cerebellar ataxia which also hindered his ability to stand but not his head and trunk control while sitting: mild dysmetria was present in the four limbs. There were no clinical signs of spasticity (Ashworth Scale grade 0/4, meaning no increase in muscle tone), although mild hyperreflexia was present in the right upper limb. Muscle strength was preserved [Medical Research Council (MRC) grade 5/5 for both upper and lower extremities, meaning normal power]. Sensibility, position sense and kinesthesia were undisturbed.

Patient M.E., was a 24-year-old female, right-handed and right-footed, with TBI that had occurred 2 years earlier, with diffuse axonal injury, severe tetra-paresis and heavily impaired gait. Standing was possible only with feet apart and for less than 30 s. Trunk and head control was good while sitting. There were signs of spasticity at the right lower limb and the patient had an equinus foot, albeit without signs of contracture (Ashworth scale grade for each limb; mean of the three segments of each limb): 3.3 right inferior limb; 2 right superior limb; 2 left inferior limb; 1 left superior limb). Muscle strength was reduced such that the joint can be moved only against gravity with the examiner's resistance completely removed (MRC grade 3/5 for both upper and lower extremities). A mild hypoesthesia was detected in the four limbs.

The patients underwent our RCGR protocol, which comprised three sessions per week over a 4-week period; each session lasted 20 min. Treatment frequency was based on existing locomotor imagery practice protocols (e.g., Dickstein et al., 2004; Dunsky et al., 2006); session duration was based on recommendations to limit motor imagery sessions to 20 min, as there is a negative relationship between effect and increased practice duration (Driskell et al., 1994). As there are no standardized guidelines for clinical motor imagery protocols, we used the existing studies on locomotor imagery practice (summarized in Malouin and Richards, 2010) to inform our protocol. The instructions were mainly oriented towards the kinesthetic, rather than the visual, aspects of the task, in order to focus the patients' attention on the proprioceptive inputs given by the robot. In the first 10 min, the patient was supported by means of the BWS system, while the robotic orthosis – set to the continuous mode – moved his/her legs, reproducing rhythmical walking patterns. The hip range of motion was 40˚ (20˚ extension and 20˚ flexion), whereas the knee range of motion was from extended knee to 60˚ flexion. During robotic gait, the therapist, in enabling the robot progression, asked the patients to mentally perform cognitive tasks aimed at focusing their conscious attention on the ongoing steps, feeling proprioceptive and kinesthetic inputs, and thinking of the mental actions needed for the mental reproduction of a movement. In order to cognitively engage the patient, the therapist stopped the robot at pre-defined time points and asked the patient to describe the position of his/her hips, knees, and feet, without looking at them[1]; afterwards, starting from that position, the patient had to imagine making some other steps, following a metronome, and then, at a random metronome stop, the patient had to describe the imagined final position of his/her limbs. During the following 10 min the patient, still with BWS but without the robotic orthosis, was placed on a platform equipped with parallel bars that (s)he could hold: there (s)he was asked to recall the kinesthetic feelings of the preceding phase and to use them to perform locomotor imagery-related tasks in the first person perspective, involving different conditions such as standing, initiating gait, walking, and walking with obstacles. At the end of this phase, the patient was asked to walk along the platform, whilst continuing to concentrate on his/her body as it moved. The RCGR protocol was administered by one of the authors of the present paper (RV), a clinical neuropsychologist working at the Centro Puzzle in Turin. During the training period, patients received their standard physiotherapy.

As clinical measures we selected: the standing balance scale (SBS; Bohannon, 1989) for balance evaluation, the Massachusetts General Hospital Functional Ambulation Classification (FAC; Holden et al., 1986) for gait function, and the Barthel Index (BI; Mahoney and Barthel, 1965) for assessment of assistance need in activities of daily living. Assessments were carried out before and after the RCGR protocol. Outcome measures were administered by an independent rater, i.e., a physiatrist who was blind with respect to the treatment applied to the patient and his/her participation in an experimental rehabilitation protocol.

fMRI PROCEDURES

In order to define the brain correlates of locomotion using fMRI, a specific task implying extension, and flexion of the ankle joint has been proposed in the current literature (Dobkin et al., 2004); its validity has been demonstrated by experimental work showing that foot extension and flexion alone generate a similar brain activation pattern to that associated with walking (see for example Sahyoun et al., 2004). Indeed, movements of other lower limb joints, such as the knee or hip, are problematic in fMRI studies, as they propagate through the vertical body plane, causing head motion. Consequently, ankle plantar- and dorsiflexion represents the gold standard fMRI paradigm for gait analysis, and thus we adopted it in our study.

During fMRI, the patient was required to perform plantarflexion (downward) and dorsiflexion (upward). At the beginning of each scanning session, patients were individually instructed on the task they were going to perform during scanning. The experimenter showed the stimuli, as well as the type, amplitude and speed of the movements required; the subject was asked to perform each movement for a few seconds. The task was performed using a block design with 12 s of rest alternating with 12 s of the active condition. In the active condition, subjects moved their right foot and left foot alternately. In the rest condition, they had to relax, without performing any movements. Movements were performed at 0.5 Hz, as this rate is similar to that of ankle movements during walking. As far the movement amplitude is concerned, the patient was asked to perform the maximal plantarflexion and then a dorsiflexion of about 20–30˚ and come back to the starting position in plantarflexion. Subjects performed the task with their shoes off and their legs slightly raised and supported by pillows. Sandbags were placed on both legs in order to limit leg movements. The stimuli were visual and represented two feet. Both feet were white

[1]Acceptable descriptions were like the following: "My right leg is ahead, with my foot flat, my knee bent, and my hip forward, while my left leg is behind, as if I was to finish a step with my right leg." Despite most of the times patients needed to be prompted by therapist's questions before producing a complete description, they showed to be good at this task, as their descriptions matched their actual legs' position in every trial.

in the rest condition, the right foot turned red and the left foot remained white when the subject had to move their right foot, and vice-versa when the subject had to move their left foot. The task lasted 5 min. It was generated using the E-Prime software (Psychology Software Tools, Inc., Pittsburgh, PA, USA). A color LCD screen projected the visual stimuli onto a rear-projection screen in the bore of the magnet. The participants viewed this screen via an angled mirror system. The stimuli were presented by IFIS-SA™(MRI Device Corporation, Waukesha, WI, USA), which also synchronized the presentation of stimuli with the fMRI scanner.

Data acquisition was performed on a 1.5 T Intera scanner (Philips Medical Systems). Functional T_2-weighted images were acquired using echoplanar (EPI) sequences, with a repetition time (TR) of 3000 ms, an echo time (TE) of 60 ms, and a 90˚ flip angle. The acquisition matrix was 64×64; the field of view (FoV) was 256 mm. For each task, a total of 100 volumes were acquired. Each volume consisted of 25 axial slices, parallel to the anterior–posterior (AC–PC) commissure line and covering the whole brain; the slice thickness was 4 mm with a 0.5-mm gap. Two scans were added at the beginning of functional scanning and the data discarded to reach a steady state magnetization before acquisition of the experimental data. In the same session, a set of three-dimensional high-resolution T_1-weighted structural images was acquired for each participant. This data set was acquired using a fast field echo (FFE) sequence, with a repetition time (TR) of 25 ms, the shortest echo time (TE), and a 30˚ flip angle. The acquisition matrix was 256×256; the FoV was 256 mm. The set consisted of 160 sagittal contiguous images covering the whole brain. The in-plane resolution was $1\ mm \times 1\ mm$ and the slice thickness was 1 mm ($1\ mm \times 1\ mm \times 1\ mm$ voxels).

We analyzed imaging data using Brain Voyager QX (Brain Innovation, Maastricht, the Netherlands). The functional data of each subject underwent the following preprocessing steps: mean intensity adjustment, head motion correction, slice scan time correction, spatial data smoothing [full width at half maximum (FWHM) = 4 mm], temporal filtering, and temporal smoothing (FWHM = 2.8 s). After preprocessing, each subject's slice-based functional scans were coregistered to their 3D high-resolution structural scan, and the 3D structural data set of each subject was transformed into Talairach space (Talairach and Tournoux, 1988). Using the anatomical–functional coregistration matrix and the determined Talairach reference points, we transformed the functional time course of each subject into Talairach space and created the volume time course. For each patient, a single-subject study design matrix was specified and the defined box-car was convolved with a pre-defined hemodynamic response function (HRF) to account for the hemodynamic delay. A statistical analysis using the general linear model was performed to yield functional activation maps during the pre- and post-tests separately. Subsequently, the general linear model was use to compare post-test activations with pre-test activations for each patient. All statistical comparisons were computed at a statistical threshold of $p < 0.05$, corrected for multiple comparisons using Bonferroni correction. We measured functional connectivity using the seed voxel method. For each patient, we selected a cluster of 10 contiguous seed voxels within the SMA of the left (dominant) hemisphere. The cluster seed included the voxel with the most task-related activity in the foot task, and significant voxels surrounding it. Time courses at each voxel of the seed cluster were averaged. Next, the time course for the seed voxel cluster was correlated with every other voxel time course in the brain. Nuisance factors were used as covariates; they included head movements in the six directions and a 50-voxel region of interest (ROI) in the cerebrospinal fluid. Voxel time courses correlating significantly ($p < 0.05$ corrected for multiple comparisons using Bonferroni correction) were considered to be functionally connected. To identify changes in connectivity between the pre- and post-test conditions, a t-test was applied on the pre- and post-test connectivity maps to determine regions with significantly different connectivity across conditions ($p < 0.05$ corrected for multiple comparisons using the Bonferroni correction).

RESULTS

CLINICAL OUTCOMES

Both patients carried out the overall program and no complications were recorded; M.E. did not complete some training sessions (i.e., in the first three sessions the patient completed the first 10 min with the robotic orthosis, but was unable to complete the second part of the training session with parallel bars) owing to a lack of postural comfort. No change in spasticity or strength were observed.

PATIENT S.R.

On the SBS the income measure was 2/10, which implies standing for 30 s. with feet apart, and the outcome measure was 3/10, which implies standing with feet in contact for less than 30 s. On the FAC, the income measure was 1/6, meaning the absence of functional ambulation (he ambulated in parallel bars only), and the outcome measure was 2/6, meaning the ability to walk 10 ft or more outside parallel bars (requiring continuous manual contact of one person). On the BI, the income measure was 55/100, and the outcome measure was 70/100. This increment of 15 points resulted entirely from improvements on all the postural/gait related items of the scale, i.e., transfers (bed to chair and back), mobility (on level surfaces), and stairs.

In summary, S.R. improved on all scales used, and these improvements were clinically significant: SBS indicated a progress from standing with feet apart to standing with feet in contact; FAC indicated a progress from non-functional ambulation to ambulation; BI indicated progresses from 25 to 50% on each gait item. Thus, after the treatment, S.R. improved both balance and gait, being able to walk outside the parallel bars.

PATIENT M.E.

On the SBS the income measure was 1/10, which implies inability to stand even with feet apart, and the outcome measure was 2/10, which implies standing for at least 30 s with feet apart. On the FAC, the income measure was 1/6, meaning the absence of functional ambulation, and the outcome measure remained unaltered. Nonetheless, while at income M.E. could not ambulate at all, at the outcome she could ambulate in parallel bars. Even if this progress cannot be detected on the physiatric scale, it is indeed clinically relevant, as it makes the patient able to do rehabilitation exercises that she was unable to perform before, with the aim of possibly walking with support. Also on the BI, income and outcome measures were the same, as the progresses of M.E. fell in between score categories and thus produced no detectable improvement.

In summary, M.E. showed an improvement in balance, with decreased back sway, and more subtle progresses in ambulation, not detectable by the physiatric scales which we used.

fMRI RESULTS

Both patients managed to perform the fMRI task. In both patients, pre-RCGR fMRI testing showed activations in the foot and leg primary motor area (M1) and in the SMA.

In both patients, comparing the spatial distribution of patterns of brain activation pre- and post-RCGR revealed extended bilateral activations in the SMA, as well as activations in the cingulate motor cortex, and in the foot somatosensory motor area (S1). In patient S.R. activations in the cerebellum also emerged. **Figure 3** shows pre- and post-training activations on a sagittal view, for each patient. **Figure 4** represents three-dimensional cortex reconstructions of the dominant hemisphere, for each patient: "green" indicates activations in the pre-training condition; "yellow" indicates activations in the post-training condition. All statistical comparisons were computed at a statistical threshold of

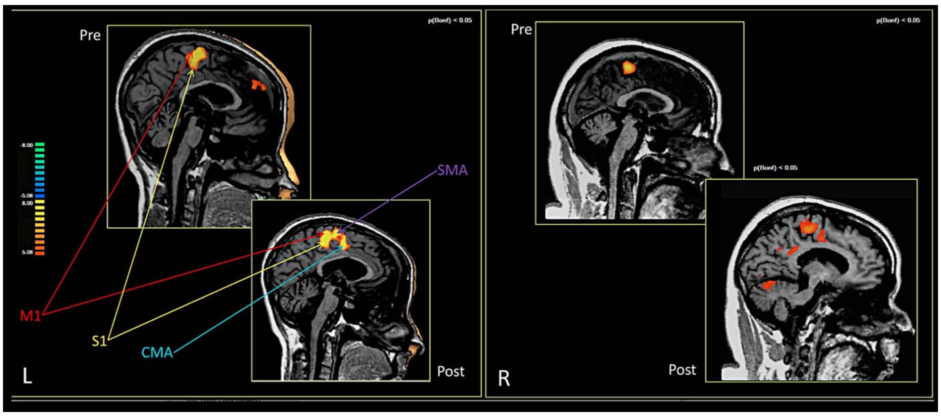

FIGURE 3 | Brain activations in the pre- and post-training conditions. Patient M.E. on the left. Patient S.R. on the right.

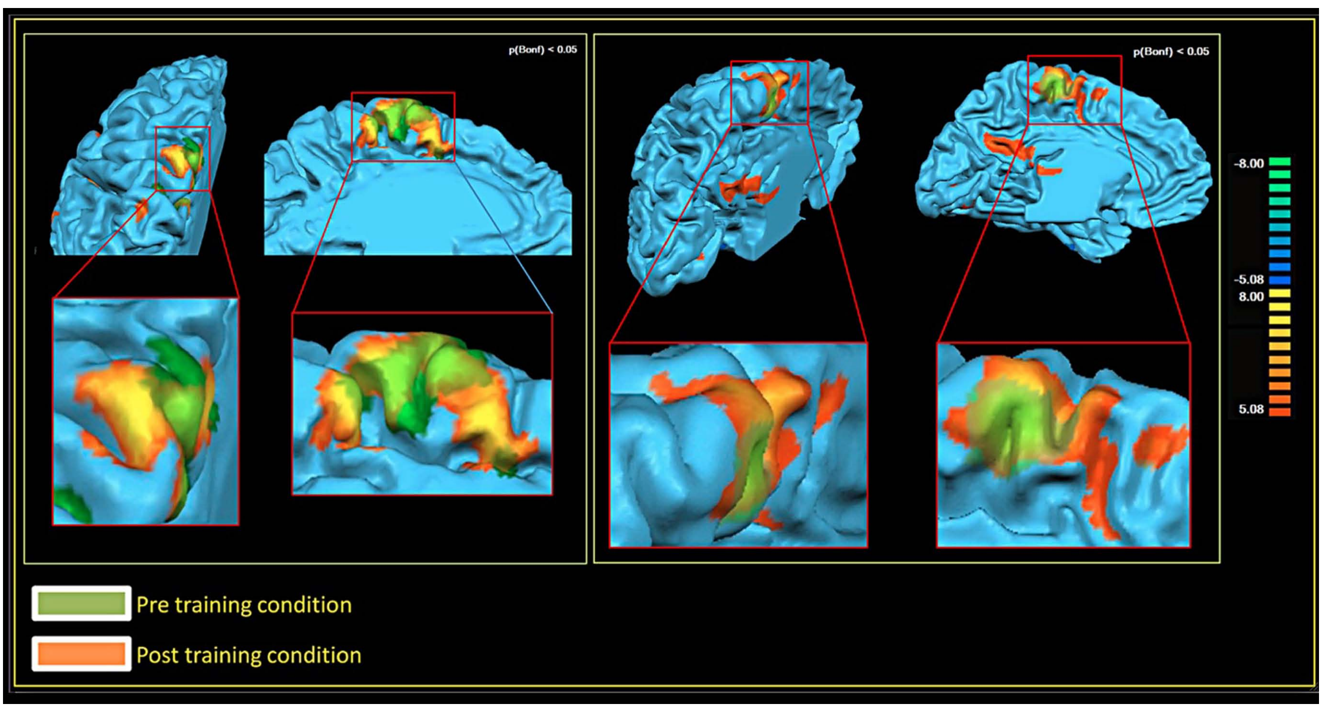

FIGURE 4 | Brain activations in the pre- and post-training conditions, 3D cortex reconstruction of the left hemisphere. Patient M.E. on the left. Patient S.R. on the right.

$p < 0.05$, corrected for multiple comparisons using Bonferroni correction.

As far as functional connectivity is concerned, it could not be computed on patient M.E. due to technical problems. It was, however, possible for S.R.: here, the seed voxel correlation analysis demonstrated an increase in functional connectivity. **Figure 5** shows the pre- and post-connectivity patterns of S. R.: "yellow" indicates connectivity in the pre-training condition; "blue" indicates connectivity in the post-training condition. All statistical comparisons were computed at a statistical threshold of $p < 0.05$, corrected for multiple comparisons using Bonferroni correction.

DISCUSSION

As we reported in the introduction, the use of RGR in subjects with brain lesions is still controversial. Indeed, these patients show gait disruption caused not only by damage to motor pathways but also by impairments of perception, attention, and body schema. For these reasons, it is important to understand the brain mechanisms leading to gait improvements. To this end, neuroimaging techniques can help in investigating the possible cerebral changes taking place during the treatment. Greater fMRI activation of cortical sensorimotor areas after RGR in incomplete spinal cord-injured patients (Winchester et al., 2005) and increased corticomotor excitability after treadmill training in chronic stroke patients (Yen et al., 2008) have been demonstrated; however, evidence of neuroplasticity after RGR in chronic brain injured patients was still lacking.

Besides, the published works investigating RGR in brain injured patients involved only stroke participants. Studies on TBI patients are lacking in the literature probably because such patients are heterogeneous in their clinical representation, usually presenting diffuse axonal damage and a focal lesion; it is therefore not easy to compare the effects across subjects. Also, unlike stroke patients in whom the gait problem is hemi-paresis/plegia, TBI patients often present para- or tetra-paresis/plegia, and this renders the therapy more complex. However, most of these patients are young and thus the treatment can benefit from a greater brain plasticity, and an efficacious rehabilitation leads to significant individual and social effects.

The present paper presented two case reports – TBI patients with major gait impairments – studied with fMRI before and after a robotic locomotor rehabilitation. Our protocol made use of a newly developed gait system specifically designed to train brain injured patients: its pneumatic actuations are intended to counter spasticity, and the absence of a treadmill should help to train patients in a more coherent perceptual framework. Together with robotic assistance, we employed motor imagery as a complementary technique. The proposed RCGR protocol should improve gait by facilitating central pattern generators and also by enhancing cognitive aspects of motor relearning. These processes should stimulate cortical neuroplasticity, investigated by fMRI.

Our neuroimaging results supported our hypotheses, showing greater activations post-training in the sensorimotor and supplementary motor cortices, as well as enhanced functional connectivity within the motor network. Such results are in line with the previous studies that we have carried out on healthy subjects (Sacco et al., 2006, 2009), as well as with the literature on motor training in normal and pathological subjects (for reviews, see Kelly et al., 2006; Rossini et al., 2007; Enzinger et al., 2008; Forrester et al., 2008). Besides, similar changes in sensorimotor and supplementary motor cortices through locomotor exercises have been associated with improved gait function in neurologically impaired children and adults (de Bode et al., 2007). Finally, the augmented connectivity, being a manifestation of the covariance of metabolic rates in functionally related brain regions, suggests a reinforcement of the strength of existing synapses.

At a clinical level, the main result we obtained was an improvement of balance, which was evident in both patients. Balance plays a major role in posture maintenance, and it is a prerequisite for ambulation; most postures demand constant sustained activity implying tone activation of muscles, designated as the tonic component of voluntary movements. It has been shown that kinetic imagery is associated with an increase of both the muscle tone and the excitability of the corticospinal pathway (Milton et al., 2008). Observations following hemispherectomy in both primates (Lawrence and Kuypers, 1968) and humans (de Bode et al., 2005) suggest that, while the phasic component of voluntary

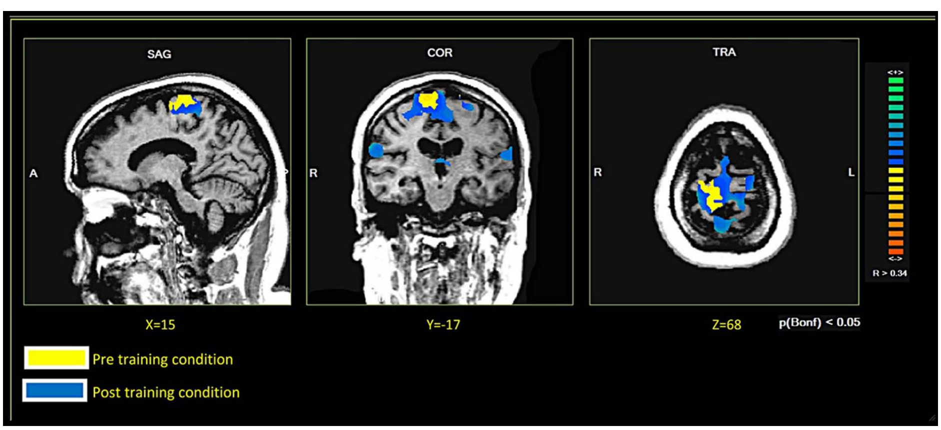

FIGURE 5 | Brain connectivity in the pre- and post-training conditions: patient S.R.

movements is most closely associated with activation in M1, the tonic component is most likely associated with activation in other cortical and subcortical regions. Kinetic motor imagery activates regions of the cortex prevalently involved in the control of the tonic components of movement (Milton et al., 2008). Thus, it is plausible that the motor imagery components of our protocol helped in improving balance. The increased post-training activations we found in the SMA and S1, together with those of the cerebellum, are consistent with such an interpretation.

As far as gait outcomes are concerned, while one patient (S.R.) showed significant improvements on all clinical scales, in the other patient (M.E.) progresses in ambulation were clinically evident but more subtle and not detectable by the physiatric rating scales we used. However, for chronic TBI subjects with major motor impairments, even minor improvements might have positive effects on the perceived quality of life. Besides, the functional neuroimaging modifications, which were also observed in patient S.R., suggest that brain mechanisms are liable to changes, which may require a greater amount of time and training to be converted to behavioral, detectable outcomes.

Finally, the robotic orthosis we developed, despite the limitations indicated below, was shown to be suitable for this kind of patient. Indeed, it could also be used with the active participation of patients, exploiting their remaining gait capacity; as active participation stimulates motor recovery, future work with this orthosis should also involve less severe TBI patients, in order to investigate the effect of the patient's active contribution.

In conclusion, our RCGR protocol appears to be a useful tool for gait rehabilitation in TBI patients, whose primary impact is on balance impairment. It may enhance both the subcortical motor automatisms and the cortical processes of motor learning. Systematic studies involving a greater number of participants and follow-up assessments are necessary in order to confirm our suggestions.

LIMITATIONS

This study is of an exploratory nature, being limited to the observation of only two patients: it demonstrates that the RCGR program can be effective for some TBI patients, but it provides no information about what proportion of such patients will benefit from its use. Thus, further systematic research is needed to address clinical outcomes. Moreover, as our RCGR protocol is a combination of robot gait and motor imagery training, we cannot differentiate the effect of the two components on brain changes; a controlled study may clarify this issue. Finally, the robotic gait system proposed here still has a few shortcomings: firstly, the lack of foot contact prevents meaningful podalic somatosensory information for postural control; secondly, it does not provide ankle motion, which would be important both for clinical reasons and for homogeneity with the fMRI task that we can use to study locomotion (as we already mentioned, fMRI tasks suitable for studying gait neural correlates involve ankle flexion): complete weight support entails less compliance. At present, we are working on the design of a new gait orthosis prototype comprising ground contact and an actuated ankle joint.

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REFERENCES

Basford, J. R., Chou, L. S., Kaufman, K. R., Brey, R. H., Walker, A., Malec, J. F., Moessner, A. M., and Brown, A. W. (2003). An assessment of gait and balance deficits after traumatic brain injury. *Arch. Phys. Med. Rehabil.* 84, 343–349.

Belforte, G., Gastaldi, L., and Sorli, M. (1997). "Active orthosis for rehabilitation and passive exercise," in *Proceedings of the International Conference on Simulations in Biomedicine*, Biomed, 199–208.

Belforte, G., Gastaldi, L., and Sorli, M. (2001). Pneumatic active gait orthosis. *Mechatronics* 11, 301–323.

Berthoz, A. (2000). *The Brain's Sense of Movement.* Cambridge, MA, London: Harvard University Press

Bohannon, R. W. (1989). Correlation of lower limb strengths and other variables with standing performance in stroke patients. *Physiother. Can.* 41, 198–202.

Colombo, G., Joerg, M., Schreier, R., and Dietz, V. (2000). Treadmill training of paraplegic patients using a robotic orthosis. *J. Rehabil. Res. Dev.* 37, 693–700.

Colombo, G., Wirz, M., and Dietz, V. (2001). Driven gait orthosis for improvement of locomotor training in paraplegic patients. *Spinal Cord* 39, 252–255.

de Bode, S., Firestine, A., Mathern, G. W., and Dobkin, B. (2005). Residual motor control and cortical representations of function following hemispherectomy: effects of etiology. *J. Child Neurol.* 20, 64–75.

de Bode, S., Mathern, G. W., Bookheimer, S., and Dobkin, B. (2007). Locomotor training remodels fMRI sensorimotor cortical activations in children after cerebral hemispherectomy. *Neurorehabil. Neural Repair* 21, 497–508.

Decety, J., and Boisson, D. (1990). Effect of brain and spinal cord injuries on motor imagery. *Eur. Arch. Psychiatry Clin. Neurosci.* 240, 39–43.

Dickstein, R., Dunsky, A., and Marcovitz, E. (2004). Motor imagery for gait rehabilitation in post-stroke hemiparesis. *Phys. Ther.* 84, 1167–1177.

Dobkin, B. H., Firestine, A., West, M., Saremi, K., and Woods, R. (2004). Ankle dorsiflexion as an fMRI paradigm to assay motor control for walking during rehabilitation. *Neuroimage* 23, 370–381.

Driskell, J. E., Copper, C. M., and Moran, A. (1994). Does mental practice enhance performance? *J. Appl. Psychol.* 79, 481–492.

Dunsky, A., Dickstein, R., Ariav, C., Deutsch, J., and Marcovitz, E. (2006). Motor imagery practice in gait rehabilitation of chronic post-stroke hemiparesis: four case studies. *Int. J. Rehabil. Res.* 29, 351–356.

Enzinger, C., Johansen-Berg, H., Dawes, H., Bogdanovic, M., Collett, J., Guy, C., Ropele, S., Kischka, U., Wade, D., Fazekas, F., and Matthews, P. M. (2008). Functional MRI correlates of lower limb function in stroke victims with gait impairment. *Stroke* 39, 1507–1513.

Forrester, L. W., Wheaton, L. A., and Luft, A. R. (2008). Exercise-mediated locomotor recovery and lower-limb neuroplasticity after stroke. *J. Rehabil. Res. Dev.* 45, 205–220.

Friston, K. J., Frith, C. D., Liddle, P. F., and Frackowiak, R. S. (1993). Functional connectivity: the principal-component analysis of large (PET) data sets. *J. Cereb. Blood Flow Metab.* 13, 5–14.

Hidler, J., Nichols, D., Pelliccio, M., Brady, K., Campbell, D. D., Kahn, J. H., and Hornby, T. G. (2009). Multicenter randomized clinical trial evaluating the effectiveness of the Lokomat in subacute stroke. *Neurorehabil. Neural Repair* 23, 5–13.

Holden, M. K., Gill, K. M., and Magliozzi, M. R. (1986). Gait assessment for neurologically impaired patients. Standards for outcome assessment. *Phys. Ther.* 66, 1530–1539.

Hornby, T. G., Campbell, D. D., Kahn, J. H., Demott, T., Moore, J. L., and Roth, H. R. (2008). Enhanced gait-related improvements after therapist-versus robotic-assisted locomotor training in subjects with chronic stroke: a randomized controlled study. *Stroke* 39, 1786–1792.

Husemann, B., Müller, F., Krewer, C., Heller, S., and Koenig, E. (2007). Effects of locomotion training with assistance of a robot-driven gait orthosis in hemiparetic patients after stroke: a randomized controlled pilot study. *Stroke* 38, 349–354.

Jackson, P. L., Doyon, J., Richards, C. L., and Malouin, F. (2004). The efficacy of combined physical and mental practice in the learning of a foot-sequence task after stroke: a case report. *Neurorehabil. Neural Repair* 18, 106–111.

Jackson, P. L., Lafleur, M. F., Malouin, F., Richards, C., and Doyon, J. (2001). Potential role of mental practice using motor imagery in neurologic rehabilitation. *Arch. Phys. Med. Rehabil.* 82, 1133–1141.

Jezernik, S., Scharer, R., Colombo, G., and Morari, M. (2003). Adaptive robotic rehabilitation of locomotion: a clinical study in spinally injured individuals. *Spinal Cord* 41, 657–666.

Karni, A., Meyer, G., Jezzard, P., Adams, M. M., Turner, R., and Ungerleider, L. G. (1995). Functional MRI evidence for adult motor cortex plasticity during motor skill learning. *Nature* 377, 155–158.

Kelly, C., Foxe, J. J., and Garavan, H. (2006). Patterns of normal human brain plasticity after practice and their implications for neurorehabilitation. *Arch. Phys. Med. Rehabil.* 87, S20–S29.

Lawrence, D. G., and Kuypers, H. G. (1968). The functional organization of the motor system in the monkey. I. The effects of bilateral pyramidal lesions. *Brain* 91, 1–14.

Li, X., Xia, H., and Guan, T. (2008). "Development of legs rehabilitation exercise system driven by pneumatic muscle actuator," in *Proceeding of the 2nd International Conference on Bioinformatics and Biomedical Engineering*, Shanghai.

Mahoney, F. I., and Barthel, D. W. (1965). Functional evaluation: the Barthel index. *Md. State Med. J.* 14, 61–65.

Malouin, F., and Richards, C. L. (2010). Mental practice for relearning locomotor skills. *Phys. Ther.* 90, 240–251.

Malouin, F., Richards, C. L., Doyon, J., Desrosiers, J., and Belleville, S. (2004). Training mobility tasks after stroke with combined mental and physical practice: a feasibility study. *Neurorehabil. Neural Repair* 18, 66–75.

Mayr, A., Kofler, M., Quirbach, E., Matzak, H., Frohlich, K., and Saltuari, L. (2007). Prospective, blinded, randomized crossover study of gait rehabilitation in stroke patients using the Lokomat gait orthosis. *Neurorehabil. Neural Repair* 21, 307–314.

Mehrholz, J., Werner, C., Kugler, J., and Pohl, M. (2007). Electromechanical-assisted training for walking after stroke. *Cochrane Database Syst. Rev.* 4, CD006185.

Milton, J., Small, S. L., and Solodkin, A. (2008). Imaging motor imagery: methodological issues related to expertise. *Methods* 45, 336–341.

Nelles, G. (2004). Cortical reorganization – effects of intensive therapy. *Restor. Neurol. Neurosci.* 22, 239–244.

Pascual-Leone, A., Grafman, J., and Hallett, M. (1994). Modulation of cortical motor output maps during development of implicit and explicit knowledge. *Science* 263, 1287–1289.

Phillips, J. P., Sullivan, K. J., Burtner, P. A., Caprihan, A., Provost, B., and Bernitsky-Beddingfield, A. (2007). Ankle dorsiflexion fMRI in children with cerebral palsy undergoing intensive body-weight-supported treadmill training: a pilot study. *Dev. Med. Child Neurol.* 49, 39–44.

Rossini, P. M., Altamura, C., Ferreri, F., Melgari, J. M., Tecchio, F., Tombini, M., Pasqualetti, P., and Vernieri, F. (2007). Neuroimaging experimental studies on brain plasticity in recovery from stroke. *Eura. Medicophys.* 43, 241–254.

Sacco, K., Cauda, F., Cerliani, L., Mate, D., Duca, S., and Geminiani, G. C. (2006). Motor imagery of walking following training in locomotor attention. The effect of "the tango lesson." *Neuroimage* 32, 1441–1449.

Sacco, K., Cauda, F., D'Agata, F., Mate, D., Duca, S., and Geminiani, G. (2009). Reorganization and enhanced functional connectivity of motor areas in repetitive ankle movements after training in locomotor attention. *Brain Res.* 1297, 124–134.

Sahyoun, C., Floyer-Lea, A., Johansen-Berg, H., and Matthews, P. M. (2004). Towards an understanding of gait control: brain activation during the anticipation, preparation and execution of foot movements. *Neuroimage* 21, 568–575.

Schwartz, I., Sajin, A., Fisher, I., Neeb, M., Shochina, M., Katz-Leurer, M., and Meiner, Z. (2009). The effectiveness of locomotor therapy using robotic-assisted gait training in subacute stroke patients: a randomized controlled trial. *PM R* 1, 516–523.

Sirigu, A., Cohen, L., Duhamel, J. R., Pillon, B., Dubois, B., Agid, Y., and Pierrot-Deseilligny, C. (1995). Congruent unilateral impairments for real and imagined hand movements. *Neuroreport* 6, 997–1001.

Talairach, J., and Tournoux, P. (1988). *Co-planar Stereotaxic Atlas of the Human Brain: 3-Dimensional Proportional System: An Approach to Cerebral Imaging.* Stuttgart: Thieme.

Waldner, A., Tomelleri, C., and Hesse, S. (2009). Transfer of scientific concepts to clinical practice: recent robot-assisted training studies. *Funct. Neurol.* 24, 173–177.

Westlake, K. P., and Patten, C. (2009). Pilot study of Lokomat versus manual-assisted treadmill training for locomotor recovery post-stroke. *J. Neuroeng. Rehabil.* 6, 18.

Winchester, P., McColl, R., Querry, R., Foreman, N., Mosby, J., Tansey, K., and Williamson, J. (2005). Changes in supraspinal activation patterns following robotic locomotor therapy in motor-incomplete spinal cord injury. *Neurorehabil. Neural Repair* 19, 313–324.

Wirz, M., Zemon, D. H., Rupp, R., Scheel, A., Colombo, G., Dietz, V., and Hornby, T. G. (2005). Effectiveness of automated locomotor training in patients with chronic incomplete spinal cord injury: a multicenter trial. *Arch. Phys. Med. Rehabil.* 86, 672–680.

Yen, C. L., Wang, R. Y., Liao, K. K., Huang, C. C., and Yang, Y. R. (2008). Gait training induced change in corticomotor excitability in patients with chronic stroke. *Neurorehabil. Neural Repair* 22, 22–30.

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Computerized training of non-verbal reasoning and working memory in children with intellectual disability

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Children with intellectual disabilities show deficits in both reasoning ability and working memory (WM) that impact everyday functioning and academic achievement. In this study we investigated the feasibility of cognitive training for improving WM and non-verbal reasoning (NVR) ability in children with intellectual disability. Participants were randomized to a 5-week adaptive training program (intervention group) or non-adaptive version of the program (active control group). Cognitive assessments were conducted prior to and directly after training and 1 year later to examine effects of the training. Improvements during training varied largely and amount of progress during training predicted transfer to WM and comprehension of instructions, with higher training progress being associated with greater transfer improvements. The strongest predictors for training progress were found to be gender, co-morbidity, and baseline capacity on verbal WM. In particular, females without an additional diagnosis and with higher baseline performance showed greater progress. No significant effects of training were observed at the 1-year follow-up, suggesting that training should be more intense or repeated in order for effects to persist in children with intellectual disabilities. A major finding of this study is that cognitive training is feasible in this clinical sample and can help improve their cognitive performance. However, a minimum cognitive capacity or training ability seems necessary for the training to be beneficial, with some individuals showing little improvement in performance. Future studies of cognitive training should take into consideration how inter-individual differences in training progress influence transfer effects and further investigate how baseline capacities predict training outcome.

Keywords: intellectual disability, training, working memory, non-verbal reasoning

INTRODUCTION

A now growing literature is showing that cognitive functions, such as working memory (WM), can be positively influenced by targeted and intensive training (Klingberg et al., 2005; Klingberg, 2010; Diamond and Lee, 2011; Morrison and Chein, 2011). Using computerized versions of training programs has allowed for the implementation of adaptive algorithms that ensures that the level of task difficulty is always challenging for the individual, something that has been shown to be crucial for the training to be effective (Klingberg, 2010). Such training has been shown to improve WM performance in healthy children and adults (Olesen et al., 2004; Jaeggi et al., 2008; Thorell et al., 2009; Bergman Nutley et al., 2011) and in children with attention-deficit hyperactivity disorder (ADHD) (Klingberg et al., 2002, 2005; Beck et al., 2010; Holmes et al., 2010; Mezzacappa and Buckner, 2010) children born preterm (Lohaugen et al., 2011) and adults recovering from stroke and other acquired brain injuries (Westerberg et al., 2007; Lundqvist et al., 2010). As the studies mentioned above show improvements in performance on WM tasks dissimilar to those trained on, this is assumed to reflect an increase in capacity and/or general skills rather than the development of task-specific strategies (Klingberg, 2010).

A cognitive function that is related to WM is reasoning ability (also referred to as fluid intelligence or reasoning, Gf) (Conway et al., 2003; Kane et al., 2004). Reasoning ability refers to the ability to identify patterns and relations and to infer rules for novel problems (Horn and Cattell, 1966). Gf is independent from skills relying on previously learnt knowledge, commonly referred to as crystallized intelligence, but is of great importance for academic achievement (Lynn et al., 2007; Alloway and Alloway, 2010). As reasoning ability is highly related to WM capacity, one hypothesis has been that effects of WM training will transfer to improvements in performance on reasoning tasks. This has indeed been observed in some studies (Klingberg et al., 2005; Jaeggi et al., 2008), while other studies have not found such effects (Holmes et al., 2009; Thorell et al., 2009; Bergman Nutley et al., 2011). The inconsistent findings may reflect variability in the demographic characteristics of the participants, such as age and clinical status, the tasks used to evaluate reasoning ability (Klingberg, 2010), as well as other factors associated with the training programs such as motivation (Jaeggi et al., 2011).

In addition, within the same training condition, inter-individual differences might be important for predicting training improvements and transfer. For example it has recently been reported that variants within the gene coding the dopamine transporter (*DAT1*) influence the degree of transfer following cognitive training (Söderqvist et al., 2012). Other studies have reported correlations between baseline cognitive capacity and improvements following training (Mackey et al., 2011) and between training progress and degree of transfer (Jaeggi et al., 2011). In clinical samples with large heterogeneity in both baseline capacity and etiology such inter-individual differences might be of particular importance as they might reflect on the capacity to learn and improve from practice.

Considering the difficulties of inducing transfer effects to reasoning ability following WM training, an alternative approach is to train directly on tasks that load highly on reasoning ability. One study assessed this by using commercially available games (Mackey et al., 2011). Two groups of children were compared: one group playing games considered to emphasize speeded responses and the other playing games considered to require reasoning abilities. Analysis of pre- and post-scores showed significant improvements on the functions being trained. In addition the reasoning training resulted in improved visuo-spatial WM.

We recently developed a computerized program targeting non-verbal reasoning (NVR) specifically (Bergman Nutley et al., 2011). The program was based on three tests from the Leiter test battery (Roid and Miller, 1997) all loading on Gf: Repeated Patterns, Classification, and Sequential Order. Similar to the WM training described above, an adaptive algorithm was used to ensure that training was performed at a level close to each participant's highest capacity and the training did not include any instructions regarding strategy use. This program was assessed in typically developing 4-year-old children who trained for approximately 15 min per session for a minimum of 20 sessions. Compared to an active control group, the training group showed significant improvements on a measure of Gf. Furthermore, training NVR resulted in transfer effects to a visuo-spatial WM task, demonstrating transfer between cognitive constructs.

One clinical group for which cognitive training could be of particular benefit is children with intellectual disabilities. In addition to impaired intelligence, these children often show impaired performance on both visuo-spatial and verbal WM (Van der Molen et al., 2009). Although WM is strongly correlated with Gf (Engle et al., 1999; Conway et al., 2003), these impairments are not mediated by Gf deficits as WM impairments remain after controlling for Gf (Van der Molen et al., 2009). Intellectual disability thus includes independent deficits in both Gf and WM, which suggest that children with such disabilities might benefit from interventions aimed to improve WM as well as NVR. A number of studies have attempted to improve WM in patients with intellectual disabilities. Initial studies focused on teaching rehearsal strategies and some studies did show that this approach can improve WM performance (Brown et al., 1973; Kramer and Engle, 1981; Conners et al., 2001, 2008). However, no advantage from teaching rehearsal strategies was found compared with training without specific strategy related instructions (Kramer and Engle, 1981). Recently a WM training program focusing on repeated and intense training without any rehearsal strategies was assessed in a population of intellectually impaired teenagers (Van der Molen et al., 2010). Training on a visuo-spatial WM task (an Odd One Out task) resulted in significantly improved performance on a compound measure of verbal WM (digit and non-word recall) directly after training had finished. Additional encouraging results emerged at a 10-week follow-up with significant improvements observed on visual WM and on measures of school achievement and story recall. However, this study did not yield significant improvements on Raven's progressive matrices, a reasoning task known to load highly on Gf. These findings suggest that it is possible to train visuo-spatial WM in intellectually impaired young people and, importantly, that such training can lead to improvements on non-trained WM tasks, also in the verbal domain.

The current study assessed training in children with intellectual disability using a combination of visuo-spatial WM and NVR training as previously used in typically developing children by Bergman Nutley et al. (2011). The first aim of the current study was to assess whether children with intellectual disability can manage the intense regime of cognitive training. Second, we aimed to evaluate if successful training in children with intellectual disability leads to improved performance on non-trained tasks. Considering the large heterogeneity of etiology and severity of symptoms within this group of children we expected a large variability in response to the intervention. The third aim was therefore to evaluate predictors of inter-individual differences in training progress and transfer.

MATERIALS AND METHODS

PARTICIPANTS

All participants had intellectual disability (IQ < 70, retrieved from clinical records) and were registered with the mental habilitation center in the area of Buskerud in Norway. Guardians of patients with intellectual disability and with a chronological age of 6–12 years were initially contacted by mail or telephone and invited to participate in the study. Informed consents were obtained from legal guardians and children before participation. Ethical approvals were received from the regional ethics committees at Oslo University and Karolinska Institutet in Stockholm. We included children aged 6–12 years, rather than older children, to ensure the program was age appropriate regarding motivational aspects. All children were pseudo-randomized into the two training groups, after controlling for chronological age and gender by independent personnel not otherwise involved with study design or implementation. The study had a double-blinded design, with participants and cognitive assessors being blind to group membership. In order to be able to generalize our results to wider clinical samples of children with intellectual disabilities, we included children with additional co-morbid diagnoses and/or taking prescribed medication. Exclusion criteria were a diagnosis of autism and severe motor and sensory problems, as these were considered to affect pre- or post assessments (and hence reliability of assessments) or training ability. For practical reasons children with guardians requiring an interpreter for conversations in Norwegian were also excluded.

COGNITIVE ASSESSMENTS

Assessments included verbal and visuo-spatial WM tasks, measures of NVR tasks loading on Gf, sustained attention, and language functioning. All tests were administered before training (T1), directly after the training period (T2), and 1 year after the training (T3). Tests were administered in the same order at all time points. A word span task was used to assess verbal short term memory (STM) and WM (Thorell and Wahlstedt, 2006). In the STM condition, a series of non-related nouns are presented verbally to the child who is required to repeat these in the correct forward order. Each trial consists of a string of words to be remembered starting with a load of two (i.e., a string of two words to be remembered), load is then increased as the participant answers correctly, with a maximum load of six. The test ends after four consecutive incorrect answers. In the WM condition, the task is changed to include manipulation of information by requiring the participant to recall strings of words in the backwards order to their presentation but with otherwise similar procedure. To assess visuo-spatial WM we used the Odd One Out task from the Automated WM Assessment (Alloway, 2007). This computerized task requires the participant to first identify the odd shape in a series of three shapes presented simultaneously in three boxes. Three empty boxes are then presented and the child has to point to that box in which the odd shape appeared. Difficulty is increased by increasing the number of series presented sequentially, and hence how many locations one needs to remember (one location for each series presented).

Two measures loading on Gf were used: Block Design from Wechsler Preschool and Primary Scale of Intelligence (WPPSI) (Wechsler, 2004) and Raven's colored progressive matrices (Raven, 1998). The Block Design task requires the participant to reproduce a visually presented pattern using red and white colored blocks. Scores are calculated based on speed and accuracy, with a maximum score of 40. The Raven's colored progressive matrices test involves completing incomplete matrices by identifying visual patterns and rules. To reduce test-retest effects and shorten the time of assessment, we administered even numbered items of Raven's colored matrices at T1 and odd numbered items at T2 and T3. The maximum score was 18. The Auditory Attention subtest from the NEPSY (Brooks et al., 2009) was used to assess sustained attention. During 3 min the participant listens to a recorded voice pronouncing list of words read with a 1 s interval and the child has to place a red foam figure in a box each time the word "red" is heard. Points are given for each correct response and withdrawn for each incorrect response (placing a red figure in the box when the word "red" was not heard, or responding to the mentioning of some other color by placing figures with that color in the box). The Comprehension of Instructions (Instructions) subtest from the NEPSY was used to assess language comprehension. The child is instructed to point to figures with certain characteristics in the same order as instructed. Task difficulty increases with number of items, number of characteristics, and their syntactic complexity.

SCHOOL ASSESSMENTS

A Norwegian translation of the Aston Index test for language disabilities (Newton and Thomson, 1982) was used to assess letter reading and writing. Number perception and calculations were assessed using the Norwegian paper-and-pencil assessment "Alle Teller" (McIntosh, 2007). These were assed directly before training and 1 year following training.

PARENT-RATED BEHAVIORAL QUESTIONNAIRES

Parents completed questionnaires at T1, T2, and T3. A Norwegian translation of The Strengths and Difficulties Questionnaire (SDQ) (Heyerdahl, 2003) was used to measure child behavior on five scales: emotional symptoms, conduct problems, hyperactivity/inattention, peer relationship problems, and prosocial behavior. A revised version of the diagnostic questions for ADHD from the DSM-IV (American Psychiatric and American Psychiatric Association, 2000) were used to assess inattention.

MOTIVATION

To assess children's motivation for performing the training programs we asked the children's parents (or teachers when the training was carried out at school) to complete an in-house questionnaire with eight questions on a 5 point scale. Questions concerned how fun, entertaining, and difficult the training was perceived by the parent/teacher and how the parent/teacher believed that the child had perceived the training.

TRAINING PROCEDURE

Training was carried out in either the participants' home with parent supervision (80% of participants) or at school with teacher supervision. Training was performed for approximately 20 min a day, 5 days a week for 5 weeks using participants' or schools' personal computers. A minimum of 20 training sessions were required for inclusion in analyses. At each training session the participants trained on two (out of three) different versions of the NVR tasks and two (out of seven) different versions of the WM tasks. The NVR tasks consisted of a display of different cards with different geometrical shapes that could be altered in a number of different parameters (e.g., color, shape, size). For each task one or two slots were empty and the participants had to allocate cards from a set of alternatives to fill these slots. The three different types of tasks were: *Repeated Patterns* that required the completion of a repeated pattern such as alternating shapes; *Sequential Order* in which a logical progression (e.g., increase in size) had to be identified to complete the pattern; and *Classification,* which required the matching of target cards to the correct alternative that matched on some parameter, such as the same color (for a more detailed description of the training paradigms see Bergman Nutley et al., 2011). The WM training program was provided by Cogmed Systems and consisted of visuo-spatial WM tasks. Colorful figures were displayed in different settings (e.g., in a pool or riding on a roller-coaster) and some of the figures made sounds (e.g., laughing) and changed color in a serial order. The task was to click on the figures in the same order as they had made a sound and changed color. The number of figures to be remembered was increased for each level. Difficulty level was automatically adjusted according to performance in the adaptive training group, but was always kept at the lowest level (one item to be remembered) in the non-adaptive training group.

Training performance was monitored by researchers via an internet server for both training groups to ensure that training was being performed and that each session lasted approximately 20 min. Furthermore, performance for the adaptive training group was monitored to assess improvements. Feedback was provided to all participants individually via e-mail once a week.

STATISTICAL ANALYSES

To test the effect of training we performed univariate general linear models in SPSS (version 20.0.0) using each of the outcome measures as a dependent variable and including T1 performance on the same measure, age, gender, group, and a group*gender interaction as independent variables. In order to account for differences in training progress and how these affect transfer, further analyses using training improvement as a continuous independent variable were performed. For the three NVR tasks we used scores of the highest levels reached on the different tasks. For the non-adaptive training group this was set to three which was the highest level their training could reach. For performance on WM training tasks we used an index improvement score based on the highest level reached, but taking into account baseline performance, measured as the performance during the second and third day of training when it is assumed that no training improvements have yet occurred. Participants in the non-adaptive training group were constantly on level one throughout the training and their index improvement was set to zero. These measures were all standardized and a mean score of these standardized scores was used to represent each participant's training progress. This measure of training progress was later also used as a dependent variable in backwards stepwise regression analyses assessing how baseline performance predicted training progress in the adaptive training group.

RESULTS

DEMOGRAPHICS

Out of 52 participants recruited, 41 were included in the analyses (22 males and 19 females), aged 6–12.5 years ($M = 9.68$, $SD = 1.58$). Children were excluded due to problems with T1 assessments (e.g., poor engagement in tasks) ($n = 3$), not completing the required 20 sessions of training ($n = 7$) and technical problems causing incomplete training data ($n = 1$). Twenty-two children were included in the adaptive training group and 19 children were included in the non-adaptive training group. Training was performed for 20–25 sessions ($M = 24.5$, $SD = 1.50$ in the adaptive training group and $M = 24.7$, $SD = 1.16$ in the non-adaptive training group).

According to parental reports, 20 participants had additional diagnoses: 9 with ADHD (non-adaptive training $n = 4$, the adaptive training $n = 5$), 2 with Down's syndrome (non-adaptive training $n = 1$, adaptive training $n = 1$), 2 with epilepsy (non-adaptive training $n = 1$, adaptive training $n = 1$), and 7 with other additional neurological diagnoses: 1 with Albrik's syndrome (adaptive training), 2 with unspecified chromosomal deviation (non-adaptive training $n = 1$, adaptive training $n = 1$), 1 with language disorder (adaptive training), 1 with Duchenne muscular dystrophy (adaptive training), 1 with Hypothalamic insufficiency (non-adaptive training), and 1 with neurofibromatosis-1 (adaptive training). Five participants were prescribed psycho stimulant medication throughout the study period (non-adaptive training $n = 2$, adaptive training $n = 3$).

T-tests revealed no significant differences in baseline performance or age between the two groups (all p-values >0.1) (**Table 1** summarize performance across groups and time-points). Similarly, Chi Square tests showed no significant differences in the distribution of gender and number of co-morbid diagnoses between the two training groups (both p-values >0.1). T-tests comparing baseline performance for the two genders showed a trend effect of males performing better than females on word span

Table 1 | Mean scores for the two training groups at the three assessment points.

	Adaptive training group			Non-adaptive training				
	T1 Mean (SD)	**T2 Mean (SD)**	**T3 Mean (SD)**	**T1 Mean (SD)**	**T2 Mean (SD)**	**T3 Mean (SD)**	**T2 Cohen's *d***	**T3 Cohen's *d***
Word span backwards	5.48 (5.29)	7.10 (6.93)	6.71 (8.19)	6.25 (7.50)	5.31 (4.80)	7.94 (8.37)	0.41	−0.07
Word span forwards	14.76 (4.62)	13.33 (5.16)	13.38 (6.64)	11.63 (5.95)	13.88 (6.35)	13.69 (6.85)	−0.15	−0.37
Odd One Out	9.59 (4.30)	11.45 (5.21)	11.09 (5.42)	10.31 (4.47)	10.38 (4.41)	11.88 (5.58)	0.40	−0.02
Block Design total	24.27 (4.23)	25.09 (5.04)	24.18 (5.12)	22.81 (4.40)	22.50 (4.76)	23.38 (6.61)	0.27	−0.15
Block Design females	25.40 (3.53)	23.80 (5.03)	24.20 (4.85)	22.14 (2.73)	20.86 (2.27)	21.29 (6.08)	−0.09	−0.1
Block Design males	23.33 (4.68)	26.17 (5.01)	24.17 (5.56)	23.33 (5.48)	23.78 (5.87)	25.00 (6.89)	0.10	−0.04
Instructions total	14.70 (4.98)	16.20 (4.65)	16.10 (4.79)	14.06 (4.80)	15.12 (4.96)	16.18 (4.73)	0.09	−0.15
Instructions females	15.25 (2.77)	17.27 (3.41)	16.50 (3.30)	13.43 (5.26)	13.14 (4.74)	16.00 (6.11)	0.55	−0.32
Instructions males	14.33 (6.13)	15.50 (5.35)	15.83 (5.70)	14.50 (4.70)	16.50 (4.86)	16.30 (3.86)	−0.16	−0.06
Auditory Attention	37.62 (22.03)	43.67 (21.89)	46.29 (18.94)	37.46 (20.03)	40.85 (22.38)	45.92 (16.66)	0.11	0.01
Raven's	8.95 (3.87)	8.15 (3.30)	8.55 (2.91)	8.00 (4.20)	7.25 (3.44)	8.19 (2.83)	−0.01	−0.15

Effect sizes of adaptive training compared to non-adaptive training are represented by Cohen's d for change from T1 at T2 and at T3. For the two tests showing gender interactions, scores are also presented for the two genders separated.

backwards [$t_{(38)} = 1.85$, $p = 0.072$]. Due to this observation we included gender as a covariate in all subsequent analyses.

MOTIVATION

Parents responded to statements about their perceptions of the training. The adaptive training group agreed to a larger extent with the statement that the training was too difficult [$\chi^2_{(4)} = 16.50$, $p < 0.05$], while the non-adaptive training group agreed to a larger degree with the statement that training was too easy [$\chi^2_{(4)} = 14.99$, $p < 0.05$], as measured with Pearson's chi-square test. However there were no significant differences between the training groups on questions regarding how entertaining or motivating the training was perceived (all p-values >0.1). Furthermore, correlating training progress within the adaptive training group revealed no significant correlations between any of the motivation parameters and training performance (all p-values >0.1).

EFFECTS OF TRAINING AT T2

Univariate general linear models were performed separately for the different outcome measures. Test performance at T2 was the dependent variable, gender, and training group were entered as factors and test performance at T1, age, and gender*training group interaction were included as covariates. Training group showed no significant effects in predicting transfer effects (word span forwards, $p = 0.960$; word span backwards, $p = 0.104$; Odd One Out, $p = 0.107$; Instructions, $p = 0.349$; Block Design, $p = 0.387$; Raven's, $p = 0.669$; Auditory Attention, $p = 0.107$). However a trend effect for the group*gender interaction was observed for the Instructions task [$F_{(1, 33)} = 3.998$, $p = 0.054$]. Significant effect of training group on the Instructions task was seen for females only [$F_{(1, 13)} = 29.49$, $p = 0.049$; compared to $F_{(1, 18)} = 4.88$, $p = 0.434$ for males].

TRAINING PROGRESS

There was large inter-individual variance in training progress within the adaptive training group (**Figure 1**). For some participants performance did not increase considerably above the levels of the non-adaptive training paradigm and for these children the training cannot be considered successful. In order to assess how differences in training progress affected transfer effects we carried out additional analyses using training progress as described above as a covariate instead of training group. General linear models were run for each outcome measure. T2 performance on each outcome measure were the dependent variables, and independent variables were T1 performance, age, gender, training progress, and a gender*training progress interaction. **Table 2** summarizes these results. Training progress predicted improvements on Odd One Out [$F_{(1, 34)} = 6.53$, $p = 0.015$] and word span backwards [$F_{(1, 33)} = 7.58$, $p = 0.010$]. For Comprehension of Instructions there was a significant effect of the gender*training progress interaction [$F_{(1, 33)} = 4.76$, $p = 0.036$], with significant effect of training progress observed for female participants only [$F_{(1, 13)} = 5.41$, $p = 0.037$; compared to $F_{(1, 18)} = 0.77$, $p = 0.391$ for males]. For Block Design we observed a trend for training*gender interaction [$F_{(1, 33)} = 3.33$, $p = 0.077$]. Effects of training were associated with improvements on Block Design in males with a trend effect [$F_{(1,17)} = 13.48$, $p = 0.062$], which was not observed in females [$F_{(1, 14)} = 0.30$, $p = 0.595$]. No significant effects of training progress were observed for improvements on word span forwards, Raven's colored matrices or for Auditory Attention (all p-values >0.1). For measures of WM, the analyses of training progress explained transfer improvements to a greater extent compared to the training group analyses. These results show that larger improvements during training were associated with greater training gains.

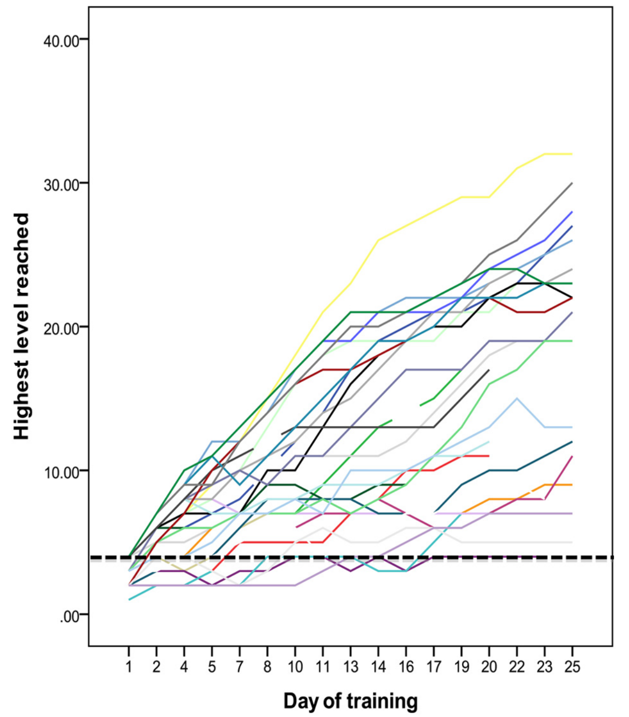

FIGURE 1 | Improvements during training on non-verbal reasoning tasks. Each line represents one participant. Highest level of performance on each training day is shown on the y-axis and the x-axis shows the training session. The dashed line indicates the highest level performed by the non-adaptive training group throughout the training period.

EFFECTS OF TRAINING AT T3

Training had no effect on outcome measures employed in this study assessing cognitive abilities or school assessments at the T3 follow-up at the group level. There were also no strong relationships between progress during training and performance at T3 (all p-values >0.1).

PARENT-RATED BEHAVIORAL QUESTIONNAIRES

No significant training related changes were observed in scores on the ADHD symptoms and the Strength and Difficulties questionnaires at T2 or T3 (all p-values >0.1).

PREDICTION OF TRAINING PROGRESS

To investigate predictors of training progress we performed backwards stepwise regression analysis including participants from the adaptive training group only. We included all cognitive measures

Table 2 | The effect of training progress on transfer effects.

Outcome measure	R^2	T1 performance *F* (*p*)	Age *F* (*p*)	Gender *F* (*p*)	Training progress *F* (*p*)	Training progress* gender *F* (*p*)
Word span backwards	0.56	**33.06 (<0.001)**	0.04 (0.837)	0.27 (0.607)	**7.58 (0.010)**	1.03 (0.317)
Word span forwards	0.47	**29.44 (<0.001)**	0.02 (0.904)	0.00 (0.961)	0.13 (0.718)	0.00 (0.981)
Odd One Out	0.69	**58.23 (<0.001)**	0.46 (0.504)	1.83 (0.185)	**6.53 (0.015)**	0.019 (0.892)
Block Design	0.56	**28.37 (<0.001)**	0.67 (0.420)	**7.22 (0.011)**	1.16 (0.289)	3.33 (0.077)
Raven's colored matrices	0.46	**6.56 (0.015)**	2.88 (0.099)	3.44 (0.072)	0.83 (0.369)	0.205 (0.654)
Comprehension of instructions	0.71	**50.51 (<0.001)**	0.44 (0.511)	1.19 (0.283)	0.717 (0.403)	**4.76 (0.036)**
Auditory Attention	0.76	**50.57 (<0.001)**	0.05 (0.833)	0.01 (0.923)	0.11 (0.744)	1.38 (0.249)

*Table shows F and p-value for the factors and covariates included in the analysis of each outcome measure: T1 performance on the outcome measure, age, gender, training progress, and training progress*gender interaction. Adjusted R^2 for each model is also presented. Significant values ($p < 0.05$) are marked in bold.*

at T1, gender, and co-morbid diagnosis as a categorical variable (yes/no) as independent variables and training progress as the dependent variable. The final model with best prediction of training progress included 5 variables: gender ($\beta = 0.573$, $p = 0.001$); backwards word span ($\beta = 0.516$, $p = 0.003$); co-morbidity ($\beta = -0.513$, $p = 0.002$); word span forwards ($\beta = 0.315$, $p = 0.069$); and Block Design ($\beta = -0.294$, $p = 0.071$). These results show that females and participants with an intellectual disability but no additional diagnosis on average had more progress during training. On cognitive tasks, high performance on the backwards and forward word span tasks was associated with greater training progress. In contrast, performance on the Block Design task was negatively associated with progress, with lower baseline performance associated with greater training progress.

DISCUSSION

The major finding of this study is that it is feasible for children with intellectual disability to undergo intensive computerized cognitive training, with more than 85% of participants completing approximately 20 min of training per session for an average of 24 (and minimum of 20) sessions. There was large variability in training performance with some participants showing little progress during training. The amount of progress during training was significantly related to improvements on transfer tasks measuring visuo-spatial and verbal WM and language comprehension. Training progress predicted improvements on both WM and language comprehension directly following training, but not at a 1-year follow-up. Training on purely visuo-spatial tasks resulted in improvements tasks assessing verbal WM and language function, thus showing transfer between cognitive constructs and modalities. This is particularly encouraging as deficits in verbal WM are observed to be more severe than visuo-spatial deficits in children with intellectual disabilities (Henry and MacLean, 2002; Van der Molen et al., 2009).

Training did not lead to significant improvements on reasoning ability tasks (Block Design and Raven's colored matrices) although a trend association was observed on improvements on Block Design for males. **Figure 2** shows improvements on a WM task (Odd One Out) and a reasoning task (Block Design) for the two groups in the current study as well as for the typically developing sample of 4-year-olds who previously completed the same training (reported in Bergman Nutley et al., 2011). As is apparent from this figure, adaptive training resulted in similar improvements in WM for the children with intellectual disability as it did for the typically developing 4-year-olds. However, in the current sample improvements on Block Design were of a smaller magnitude and with larger variability compared to the typically developing sample. This suggests that reasoning ability is more difficult to improve with training in this clinical group, perhaps due to this deficit being particularly impaired in children with intellectual disability.

The importance of training progress for transfer has recently also been demonstrated by Jaeggi et al. (2011), who showed that transfer effects following WM training were dependent on improvements observed during training in typically developing children. However, no significant relation between baseline capacity and training performance was found, thus failing to explain what determined successful training for the participants. This emphasizes the importance of studying inter-individual differences in how cognitive training is received, which has been overlooked in the majority of previous training studies. Increased understanding of this can be of great importance for guiding the future development of cognitive training programs and practices. It might be of particular importance in clinical groups that show large heterogeneity in etiology and baseline capacity, as examined in the current study.

In the clinical group currently studied, performance on the verbal WM task at baseline together with co-morbid diagnosis and gender were the strongest predictors of training progress, suggesting that verbal WM is of particular importance. Considering the evidence that verbal WM is specifically impaired in populations with intellectual disabilities (Van der Molen et al., 2009), performance on the verbal WM task might be an indication of severity of impairment, which in turn might affect the susceptibility to training induced plasticity. In general we observed that high performance at baseline was associated with larger progress during training and a higher level of transfer effects. Similar findings were found by Conners et al. (2008) for a verbal rehearsal task in children with Down's syndrome.

One possible explanation for the lack of progress for participants with low baseline scores could be that baseline capacity for these children falls under some threshold required to perform the tasks in the program. In order to assess this we compared baseline performance, on study-overlapping tasks, with that of

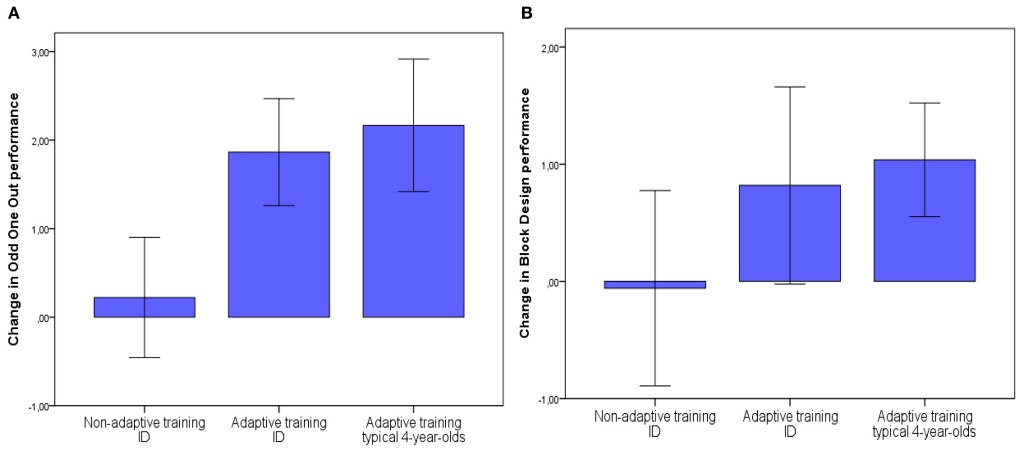

FIGURE 2 | Mean improvements following training (T2−T1) on Odd One Out (A) and Block Design (B) for the two training groups of children with intellectual disability (ID) and the adaptive (combination) training group of typically developing 4-year-olds as reported in Bergman Nutley et al. (2011). Error bars show +/− 1 standard error of the mean.

the typically developing 4-year-olds participating in the Bergman Nutley et al. (2011) study, who did show transfer effects. We found that, at baseline, participants in the current study performed equally well or significantly higher on measures of visuo-spatial WM (Odd One Out) and on measures of fluid intelligence (Block Design and Raven's colored matrices). This implies that the problem for the low performing group in this study is not related to their low baseline capacity *per se*. Rather, it is suggested that their relative low baseline capacity reflects a reduced level of plasticity that leads to smaller effects of transfer compared to that observed for the typically developing 4-year-olds. Perhaps participants with low level of plasticity require alternative methods of training, such as changed length of training period or changes in the adaptive algorithm that would allow a slower progress and therefore more practice on each level. It may also be beneficial to focus training on one construct (WM or NVR) at a time, allowing for more time being spent training on either one. This is supported by previous findings that amount of transfer seems to follow linearly from amount of time spent training that construct (Bergman Nutley et al., 2011). These issues are for future studies to investigate.

Furthermore, whether the predictive power of high baseline capacity relating to greater progress during training and larger transfer effects is special for clinical populations like this or can be generalized to healthy populations requires more in-depth investigations as some studies suggest the opposite pattern. For example, Mackey et al. (2011) found that typically developing children with lower Gf scores at baseline gained more from training than those starting with higher Gf scores. One possible explanation is that the association with poorer performance on baseline measures and larger gains in Gf reflects a regression toward the mean effect; that is, children who by chance perform below their optimal level at baseline (due to uncontrolled confounders such as energy levels, motivation, and current health status) are more likely to perform closer to their optimal level at the follow-up assessments. We take this into consideration in the current study by controlling for baseline performance in our analyses.

A concern when interpreting our results is whether the larger transfer effects we see for high performing individuals are in fact a result of the training related improvements, or whether these effects reflect a general higher level of plasticity in the high performing group, resulting in higher test-retest effects. If the latter was the case we would also expect there to be a positive correlation between baseline performance and improvements on T2 measures in the non-adaptive training group. This was not observed; rather as would be expected with a regression toward the mean effect, all significant correlations were negative indicating that lower performance on T1 measures was associated with higher gains in performance on T2 measures.

Further investigation is needed to better understand the role of co-morbid diagnoses and gender. It is at the moment not clear to us why gender would have such a strong influence in predicting training effects as we observed here, and these findings need further replication and investigation. Other factors that we were not able to control for in this study but are likely to influence training effects are underlying etiology and genetic variability.

We did not observe significant training effects at the 1-year follow-up. This suggests that training in children with intellectual disability needs to be more extended (e.g., 10 weeks instead of 5) or repeated (e.g., 5 weeks every 3 months) in order for effects to be maintained. It is not clear what frequency and intensity would be required or whether this is specific for children with intellectual disability or would also generalize to other clinical and non-clinical groups of children.

In summary, we provide new encouraging evidence that cognitive functions can be trained and improved in some children with intellectual disability. We also highlight the importance of looking at inter-individual differences in training performance and show that these predict transfer effects resulting from the training. Understanding who benefits from which type of training can help in developing future training programs to be better adapted to different individual capacities.

REFERENCES

Alloway, T. P. (2007). *Automated Working Memory Assessment Manual*. Oxford: Harcourt.

Alloway, T. P., and Alloway, R. G. (2010). Investigating the predictive roles of working memory and IQ in academic attainment. *J. Exp. Child Psychol.* 106, 20–29.

American Psychiatric and American Psychiatric Association, A., and American Psychiatric Association. Task Force On, D.-I. (2000). *Diagnostic and Statistical Manual of Mental Disorders: DSM-IV-TR*. Washington, DC: American Psychiatric Association.

Beck, S. J., Hanson, C. A., Puffenberger, S. S., Benninger, K. L., and Benninger, W. B. (2010). A controlled trial of working memory training for children and adolescents with ADHD. *J. Clin. Child Adolesc. Psychol.* 39, 825–836.

Bergman Nutley, S., Soderqvist, S., Bryde, S., Thorell, L. B., Humphreys, K., and Klingberg, T. (2011). Gains in fluid intelligence after training non-verbal reasoning in 4-year-old children: a controlled, randomized study. *Dev. Sci.* 14, 591–601.

Brooks, B. L., Sherman, E. M. S., and Strauss, E. (2009). NEPSY-II: a developmental neuropsychological assessment, second edition. *Child Neuropsychol.* 16, 80–101.

Brown, A. L., Campione, J. C., Bray, N. W., and Wilcox, B. L. (1973). Keeping track of changing variables: effects of rehearsal training and rehearsal prevention in normal and retarded adolescents. *J. Exp. Psychol.* 101, 123–131.

Conners, F. A., Rosenquist, C. J., Arnett, L., Moore, M. S., and Hume, L. E. (2008). Improving memory span in children with Down syndrome. *J. Intellect. Disabil. Res.* 52, 244–255.

Conners, F. A., Rosenquist, C. J., and Taylor, L. A. (2001). Memory training for children with Down syndrome. *Downs Syndr. Res. Pract.* 7, 25–33.

Conway, A. R., Kane, M. J., and Engle, R. W. (2003). Working memory capacity and its relation to general intelligence. *Trends Cogn. Sci.* 7, 547–552.

Diamond, A., and Lee, K. (2011). Interventions shown to aid executive function development in children 4 to 12 years old. *Science* 333, 959–964.

Engle, R. W., Tuholski, S. W., Laughlin, J. E., and Conway, A. R. (1999). Working memory, short-term memory, and general fluid intelligence: a latent-variable approach. *J. Exp. Psychol. Gen.* 128, 309–331.

Henry, L. A., and MacLean, M. (2002). Working memory performance in children with and without intellectual disabilities. *Am. J. Ment. Retard.* 107, 421–432.

Heyerdahl, S. (2003). SDQ - Strength and Difficulties Questionnarie: en orientering om et nytt spørreskjema for kartlegging av mental helse hos barn og unge, brukt i UNGHUBRO, OPPHED og TROFINN. *Norsk Epidemiologi* 13, 127–135.

Holmes, J., Gathercole, S. E., and Dunning, D. L. (2009). Adaptive training leads to sustained enhancement of poor working memory in children. *Dev. Sci.* 12, F9–F15.

Holmes, J., Gathercole, S. E., Place, M., Dunning, D. L., Hilton, K. A., and Elliott, J. G. (2010). Working memory deficits can be overcome: Impacts of training and medication on working memory in children with ADHD. *Appl. Cogn. Psychol.* 24, 827–836.

Horn, J. L., and Cattell, R. B. (1966). Refinement and test of the theory of fluid and crystallized general intelligences. *J. Educ. Psychol.* 57, 253–270.

Jaeggi, S. M., Buschkuehl, M., Jonides, J., and Perrig, W. J. (2008). Improving fluid intelligence with training on working memory. *Proc. Natl. Acad. Sci. U.S.A.* 105, 6829–6833.

Jaeggi, S. M., Buschkuehl, M., Jonides, J., and Shah, P. (2011). Short- and long-term benefits of cognitive training. *Proc. Natl. Acad. Sci. U.S.A.* 108, 10081–10086

Kane, M. J., Hambrick, D. Z., Tuholski, S. W., Wilhelm, O., Payne, T. W., and Engle, R. W. (2004). The generality of working memory capacity: a latent-variable approach to verbal and visuospatial memory span and reasoning. *J. Exp. Psychol. Gen.* 133, 189–217.

Klingberg, T. (2010). Training and plasticity of working memory. *Trends Cogn. Sci.* 14, 317–324.

Klingberg, T., Fernell, E., Olesen, P. J., Johnson, M., Gustafsson, P., Dahlstrom, K., et al. (2005). Computerized training of working memory in children with ADHD - a randomized, controlled trial. *J. Am. Acad. Child Adolesc. Psychiatry* 44, 177–186.

Klingberg, T., Forssberg, H., and Westerberg, H. (2002). Training of working memory in children with ADHD. *J. Clin. Exp. Neuropsychol.* 24, 781–791.

Kramer, J. J., and Engle, R. W. (1981). Teaching awareness of strategic behavior in combination with strategy training: effects on children's memory performance. *J. Exp. Child Psychol.* 32, 513–530.

Lohaugen, G. C., Antonsen, I., Haberg, A., Gramstad, A., Vik, T., Brubakk, A. M., and Skranes, J. (2011). Computerized working memory training improves function in adolescents born at extremely low birth weight. *J. Pediatr.* 158, 555–561.

Lundqvist, A., Grundstrom, K., Samuelsson, K., and Ronnberg, J. (2010). Computerized training of working memory in a group of patients suffering from acquired brain injury. *Brain Inj.* 24, 1173–1183.

Lynn, R., Meisenberg, G., Mikk, J., and Williams, A. (2007). National IQs predict differences in scholastic achievement in 67 countries. *J. Biosoc. Sci.* 39, 861–874.

Mackey, A. P., Hill, S. S., Stone, S. I., and Bunge, S. A. (2011). Differential effects of reasoning and speed training in children. *Dev. Sci.* 14, 582–590.

McIntosh, A. (2007). *Alle Teller!* Oslo, Norway: Matematikksenteret.

Mezzacappa, E., and Buckner, J. (2010). Working memory training for children with attention problems or hyperactivity: a school-based pilot study. *Sch. Ment. Health* 2, 202–208.

Morrison, A. B., and Chein, J. M. (2011). Does working memory training work? The promise and challenges of enhancing cognition by training working memory. *Psychon. Bull. Rev.* 18, 46–60.

Newton, M. J., and Thomson, M. E. (1982). *Aston Index: A Classroom Test for Screening and Diagnosis of Language Difficulties, Age from 5 to 14 years.* Wisbech: Learning Development Aids.

Olesen, P. J., Westerberg, H., and Klingberg, T. (2004). Increased prefrontal and parietal activity after training of working memory. *Nat. Neurosci.* 7, 75–79.

Raven, J. C. (1998). *Manual for Raven's Progressive Matrices*. Oxford: Oxford Psychologists Press.

Roid, G. H., and Miller, L. J. (1997). *Leiter International Performance Scale-Revised: Examiner's Manual.* Wood Dale, IL: Stoelting Co.

Söderqvist, S., Nutley, S. B., Peyrard-Janvid, M., Matsson, H., Humphreys, K., Kere, J., et al. (2012). Dopamine, working memory, and training induced plasticity: Implications for developmental research. *Dev. Psychol.* 48, 836–843.

Thorell, L. B., Lindqvist, S., Bergman Nutley, S., Bohlin, G., and Klingberg, T. (2009). Training and transfer effects of executive functions in preschool children. *Dev. Sci.* 12, 106–113.

Thorell, L. B., and Wahlstedt, C. (2006). Executive functioning deficits in relation to symptoms of ADHD and/or ODD in preschool children. *Infant Child Dev.* 15, 503–518.

Van der Molen, M. J., Van Luit, J. E., Jongmans, M. J., and Van der Molen, M. W. (2009). Memory profiles in children with mild intellectual disabilities: strengths and weaknesses. *Res. Dev. Disabil.* 30, 1237–1247.

Van der Molen, M. J., Van Luit, J. E., Van der Molen, M. W., Klugkist, I., and Jongmans, M. J. (2010). Effectiveness of a computerised working memory training in adolescents with mild to borderline intellectual disabilities. *J. Intellect. Disabil. Res.* 54, 433–447.

Wechsler, D. (2004). *Wechsler Preschool and Primary Scale of Intelligence - third edition (WPPSI-III).* New York, NY: Psychological Corporation.

Westerberg, H., Jacobaeus, H., Hirvikoski, T., Clevberger, P., Ostensson, M. L., Bartfai, A., et al. (2007). Computerized working memory training after stroke–a pilot study. *Brain Inj.* 21, 21–29.

Conflict of Interest Statement: Sissela B. Nutley and Torkel Klingberg are co-applicants on an international patent application for the non-verbal reasoning program, which has been financed by Pearson Assessment. Sissela B. Nutley has an employment at Pearson Assessment, who distributes the working memory training program. The other authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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