frontiers | Frontiers in Education

TYPE Original Research
PUBLISHED 03 March 2025
DOI 10.3389/feduc.2025.1490097

OPEN ACCESS

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RECEIVED 02 September 2024
ACCEPTED 10 February 2025
PUBLISHED 03 March 2025

CITATION
Rothe J, Schulte-Körne G, Hasselhorn M and Visser L (2025) The relation between parent-reported fine motor skills and spelling performance in different test modes.
Front. Educ. 10:1490097.
doi: 10.3389/feduc.2025.1490097

The relation between parent-reported fine motor skills and spelling performance in different test modes

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Background: Children are using digital devices earlier and more frequently than they did years ago. At the same time fine motor skills and the spelling performance of primary school children have deteriorated over the last years. There is some evidence for a relationship between fine motor skills and spelling performance, while the role of test mode in this context is still unknown. Therefore, the aim of the present study was to evaluate the relation between parent-reported fine motor skills and spelling performance in different test modes.

Methods: The spelling performance of German children in 3rd and 4th grade (age: 8–12 years) was examined, first in digital test mode (N = 3,453; 49.1% girls) and then in paper-pencil mode (N = 225; 44% girls). Fine motor skills were assessed using a parental questionnaire.

Results: The results confirm earlier findings of a positive relation between spelling performance and fine motor skills and reveal that using digital test mode leads to neither an immediate improvement nor a deterioration in spelling performance in children with low fine motor skills. Below-average fine motor skills appeared to have a more adverse effect on spelling performance in girls than in boys. Also, fine motor skills had an influence on school grade in German over and above its influence on reading and spelling abilities.

Conclusion: Switching from paper-pencil to digital testing does not seem to bring immediate improvement for children with low fine motor skills, but is not a disadvantage either.

KEYWORDS

handwriting, keyboard, paper-pencil, digital testing, fine motor difficulties

1 Introduction

Between 1997 and 2007, an increase in the prevalence of motor deficits, especially in fine motor skills, had been observed in German preschool children. Motor skills can be differentiated into gross ("involving the larger muscle groups") and fine motor skills (which are based on the "control of the hand, fingers and thumb, and ultimately is aimed toward the skills of handwriting and typing"; Johnson, 2012, p. 27). Already in 2007, almost every 5th

child was found to have such deficits (Stich, 2009) that can culminate in developmental coordination disorder (DCD) if there is a significant and persistent impairment of activities in daily live. While boys are more likely to be impaired in fine motor skills, girls are more likely to be impaired in gross motor and ball skills (Rodrigues et al., 2019). Fine motor skills are related to academic achievement (Wang and Wang, 2024), especially graphomotor skills as a subset of fine motor skills that relate to manual tasks with a writing tool (e.g., handwriting; Suggate et al., 2016).

In this context, it is striking that a trend similar to that for fine motor skills can also be seen in spelling performance. Spelling refers to the ability to correctly form words based on letters. From 2016 to 2021 the spelling performance of German fourth-graders has decreased significantly. In 2021, around every 3rd child did not reach the minimum standards for spelling performance, which is 8% more than in 2016 (Stanat et al., 2022). Girls outperform boys in spelling skills. Overall, the trends in motor skills and spelling performance indicate that an increasing proportion of children fall below age-appropriate levels, without considering the criteria for clinical diagnoses, highlighting a high practical relevance for educators.

1.1 Relation between motor skills and spelling performance

Fluent and correct writing (handwriting or typing) is a complex process that requires the integration of fine motor and language skills. The relationship between fine motor skills and spelling performance has been hardly investigated to date, especially in an early stage of writing development when the required fine motor skills are not yet automated. However, it is to be expected that if the fine motor skills as the lower-level cognitive part of the writing process are not yet automated, this will impair spelling performance as the higher-level cognitive part of the writing process. As motor planning seems to have priority access to working memory (Schütz and Schack, 2020), the increased effort required to plan and perform the writing movement leaves less working memory capacity for the retrieval of spelling. From this theoretical perspective, increased motor effort is needed in the early stage of writing development, as the required fine motor skills are not automatized. Children therefore initially learn to write individual letters until the involved fine motor skills and the letter-sound correspondences become automatized. Children then learn to write phonetic words (initially via the non-lexical route) and non-phonetic words (lexical route). The lexical and fine motor skills involved become increasingly automatized. Based on this developmental perspective, the automatization deficit hypothesis, originally formulated to explain symptoms of dyslexia (Nicolson and Fawcett, 1990), suggests that a generalized automatization deficit may underlie the developing difficulties in both motor skills and spelling. An increased motor effort when writing, which places a greater load on working memory, not only occurs during the early stages of writing development in general but also persists in children with fine motor difficulties (e.g., motor coordination disorders).

Few studies examine the relation between graphomotor automatization and spelling from this developmental perspective (Danna et al., 2022; Wicki et al., 2014). Danna et al. (2022) found that the relation between graphomotor skills and spelling depends on the graphomotor automatization as the relation disappears with advanced graphomotor automatization. For children with low fine motor skills and therefore less advanced graphomotor automatization, the results of Danna et al. (2022) might imply that impairments in fine motor skills (e.g., handwriting) affect spelling performance above first grade.

Further studies conversely indicate that in a stage of advanced graphomotor automatization (3th to 9th grade) spelling performance seems to contribute to handwriting speed (Downing and Caravolas, 2023; Pontart et al., 2013). Conclusions about the nature of the relation and the interaction between graphomotor skills and spelling performance are limited due to the cross-sectional design of the studies mentioned above.

Another hypothesis relevant to the relation between motor skills and spelling performance is the inhibitory deficit hypothesis, which states that impairments in motor skills are caused by compromised inhibitory control in motor tasks (He et al., 2018). It is supported by numerous findings of compromised response inhibition and attentional inhibition in individuals with DCD (Lachambre et al., 2021; Wilson et al., 2017). However, response inhibition has hardly been considered in research investigating the relation between motor skills and spelling performance. Some studies suggested a mediating role of executive functions (which include response inhibition and working memory, among others) in the relation between motor skills and reading and spelling, but response inhibition appears to be less important than working memory in the mediation (Khoury-Metanis and Khateb, 2023; Lê et al., 2021; Michel et al., 2019). The finding that working memory mediates the relation between motor skills and reading and spelling (more strongly than response inhibition) is consistent with the assumption that an increased motor effort during writing leaves less working memory capacity for spelling retrieval.

However, it is unlikely that neurodevelopmental problems like motor or spelling difficulties can be explained based on an automatization or inhibition deficit alone (McGrath et al., 2020). It is more likely that neurodevelopmental problems are a consequence of a combination of risk factors (Pennington, 2006), and therefore the combination of different types of neurodevelopmental problems is based on the presence of shared risk factors (McGrath et al., 2020). A study of Cummine et al. (2015) provides further insight into the relation between motor skills and spelling performance by examining rapid automatized naming (RAN) and reading, both evidently related to spelling. Although it is controversial whether RAN is an aspect of automatism or efficiency, the results show that RAN and reading activate similar neural networks which includes regions associated with motor planning (Cummine et al., 2015), supporting the idea of a multiple deficit model.

Although many studies control for gender, gender differences with respect to the relation between motor skills and spelling performance has not been studied directly. However, girls' spelling performance seems to be more strongly related to visuospatial skills (visuospatial short-term memory), while boys' spelling performance is more strongly related to verbal skills (verbal working memory; Adams et al., 2015). Therefore, a stronger relation between motor skills and spelling performance could be expected for girls compared to boys.

Abbreviations: ADHD, Attention deficit hyperactivity disorder; DCD, Developmental coordination disorder; EDF, Estimated degrees of freedom; GAM, Generalized additive models; GLM, Generalized linear model; RAN, Rapid automatized naming; ToS, Tablet or smartphone.

1.2 Motor skills and test mode effects

At school, children spend a substantial amount of time (30–60%) performing fine motor tasks, with paper-pencil (PP) tasks accounted for 17–37%, including handwriting with 3–18% (Caramia et al., 2020; McHale and Cermak, 1992). Children with fine motor impairments struggle with such tasks, which negatively affects their academic performance (e.g., fluency in handwriting predicts written expression). The latest International Computer and Information Literacy Study 2018 (Eickelmann et al., 2019) revealed that only a low proportion of German secondary school students (4.4% of eight graders; international mean 17.7%, European Union mean 19.7%) use digital devices in school every day. This means that even in secondary school (and therefore also in primary school), handwriting is more dominantly used than typing. However, the role of fine motor skills in everyday school life has begun to change, which is ongoing process in which children will increasingly have to read and write in a digital format in everyday school life, for homework and tests.

Changes in (test) format can lead to changes in the psychometric properties of a measurement (*test mode effects;* Goldhammer et al., 2018) and thereby affect children's performance. Even if the contents of the two test formats are identical, changes due to format requirements (e.g., the order or arrangement of tasks and items), handling (e.g., text entry via keyboard vs. handwriting) or experience in handling the test medium can affect test performance. For instance, results of the National Assessment of Educational Progress (NAEP) program indicated that computer familiarity accounts for additional variance in online essay writing performance after controlling for paper essay writing skill (Horkay et al., 2006). There is research on test mode effects in different domains, such as reading speed, reading comprehension, and mathematics (e.g., Clinton, 2019; Delgado et al., 2018; Elliott et al., 2020; Kong et al., 2018; Noyes and Garland, 2003). For spelling performance of children in general, test mode effects have hardly been studied (e.g., Feng et al., 2019), but can be assumed as handwriting and typing require different motor skills. While handwriting is more related to visual motor integration and spatial perception, typing is more related to bilateral coordination as well as motor and visual memory functions (Preminger et al., 2004). The relevance of visual-motor integration for handwriting rather than typing was confirmed in a recent study of a sample of adolescents with automated handwriting but less typing experience (Cerni and Job, 2024). The study further finds that spelling processing differs between handwriting and typing, with longer latencies for typing before starting to write and between two consecutive letters. In addition, the study reveals stronger lexicality effects for typing compared to handwriting. The results indicate an anticipated sensorimotor programming before and during typing as well as a decreasing impact of central processes on automatized skills (i.e., handwriting). For children with low fine motor skills specifically, it is still unclear whether they can achieve better spelling performance when they write with a keyboard instead of handwriting. We identified only one study, of which the results showed that children with dysgraphia (as well as children with dyslexia) make fewer spelling errors when writing with a keyboard than when writing with a stylus (Beers et al., 2018). Since visual-motor integration is a salient marker of motor impairment (Lalanne et al., 2012), which is also relevant for handwriting but less so for typing, this could explain the better spelling performance in typing compared to handwriting in children with fine motor difficulties.

Although we are not aware of any study that has investigated the relationship between smartphone or tablet ownership by children and their typing skills, the data from a recent representative study of children aged 6–13 in Germany suggests such a relationship (Feierabend et al., 2023). The number of children who state that they are good at sending messages and the number of children who state that they are texting daily or almost daily is almost the same as the number of children who have their own smartphone and increases in the same proportion with increasing age. For example, 27% of children aged 8–9 years, 58% of children aged 10–11 years and 81% of children aged 12–13 years state that they have their own smartphone. A similar number of children reported that they were good at sending messages (8–9 years: 37%, 10–11 years: 64%, 12–13 years: 88%) and texting daily or almost daily (8–9 years: 34%, 10–11 years: 47%, 12–13 years: 57%).

1.3 Study aims

To further explore effects of fine motor skills on spelling performance in different test modes, the current study had three aims.

First, we evaluated whether parent-reported fine motor skills are related to spelling performance when writing with a keyboard. We hypothesized a weaker relation between the reported fine motor skills and spelling performance during typing for children with low fine motor skills than for children with at least average fine motor skills evidenced by better fits for a non-linear model than a linear model. We assume that, below a certain level of reported fine motor skills, the higher motor effort during writing leaves less working memory capacity for the retrieval of information needed for spelling and thus the negative effect of fine motor skills on spelling performance diminishes as fine motor skills continue to decline. We expected girls' spelling performance to be more strongly related to low fine motor skills than boys' spelling performance (Adams et al., 2015). We further expected that owning a tablet or smartphone is related to time spend with a tablet or smartphone and with the usage of the tablet or smartphone which in turn leads to improved familiar-handling when writing with a keyboard and thus a lower load on working memory from the motor task of typing (e.g., bilateral coordination). This could have a beneficial effect on spelling performance when writing with a keyboard, with a more beneficial effect in children with at least average fine motor skills. Taken together, we expected a non-linear relation between fine motor skills and spelling accuracy, which also interacts with the child's sex and ownership of a tablet or smartphone.

Second, we examined whether test mode effects were pronounced differently in children with below and at least fine motor skills. Since visual motor integration as a salient marker for motor impairments (Lalanne et al., 2012) is more relevant for handwriting but less for typing (Preminger et al., 2004), we expected that children with low fine motor skills would need to put more motor effort into handwriting compared to typing and therefore achieve better spelling performance when writing with a keyboard (online assessment) instead of in PP form (as was demonstrated by Beers et al., 2018), as reflected in a smaller test repetition effect and thus a smaller raw score difference. We also took into account

children's ownership of an own tablet or smartphone and sex. We expected a greater repetition effect (greater differences in raw scores) between online and PP tests for children who own a tablet or smartphone than for children who do not, due to the benefits of familiarity with the device and better motor skills required for typing. Regarding gender, we expected the same test repetition effect for girls and boys.

Thirdly, we investigated whether fine motor skills account for the variability in school grades in the subject German beyond spelling and reading performance, which, along with listening comprehension, are the most important measures of grades in the subject German in primary school children (KMK – Kultusministerkonferenz, 2022). The expectation was that this would be the case. Based on the automatization deficit hypothesis, the increased motor effort during writing due to low fine motor skills lead to a reduced remaining working memory capacity. As a consequence, low fine motor skills would not only lead to reduced spelling performance (and consequently to lower school grades), but also to reduced performance in other areas of the subject German (e.g., grammar, text composition).

2 Methods

Families were initially invited to participate in an online study on comorbidities between specific learning disorders and psychopathology in elementary school children. For data collection, a software company (Meister Cody GmbH) has transferred various performance tests and questionnaires into an app format.

2.1 Data collection

In order to obtain a representative sample of 3rd and 4th grade children in Germany, 52,734 families with a child in 3rd or 4th grade in the German states Hesse and Bavaria were invited to participate in the study by letter via the local governments. In these letters, families obtained data to log in to the study's app via a tablet or smartphone, where they could give informed consent for their participation.

The tasks and questionnaires for the children were divided into blocks of 30–45 min per day on four different days and were carried out within the app via a tablet or smartphone from home. The spelling test (see below) was completed on the third day. Parents filled in various questionnaires, of which one focussed on motor skills of the child. Parents also reported the child's latest school grade in the subject German.

After the online study was finished, a subsample of the participating families was invited for a PP assessment in which the spelling test, among others, was completed in PP form. In Hesse, all participating families had the opportunity to participate in the PP assessment. All families who declared their interest by ticking a checkbox at the end of the online study were invited for the PP assessment. In Bavaria, only a selection of the families was invited for the PP assessment. More specifically, 177 families of children with a below-average achievement ($T \leq 40$) in reading, spelling, or math in the online studies as well as 112 families of children with average achievement were invited by letter (balanced for grade and gender). In both states, the tests were administered by trained student assistants and were held in the Leibniz Institute for Research and Information in Education and the Child and Adolescent Psychiatry of the University Hospital Munich.

The online study took place in May 2017; the PP assessments from June to September 2017 (Hesse) and from October 2017 to the beginning of January 2018 (Bavaria). Therefore, at the time of the PP assessments in Bavaria, the children had already moved to the next school grade (4th and 5th grade). Between the online and PP tests, there was a time interval of 102 days on average ($SD = 62$; range = 19–237). The study was reviewed and approved by the local ethics committees of both sites (Bavaria: project ID 438–16; date of approval 25.08.2016; Hesse: project ID FoeDises; date of approval 02.04.2017).

2.2 Sample

A total of 4,542 families have started the application (response rate 8.6%). In 921 cases, the spelling test or DCD questionnaire was not completed or the spelling data were implausible. For details about the plausibility checks please see Visser et al. (2020). We excluded the data of one sibling per pair ($n = 41$; randomly). The total sample comprised 3,580 children who completed the spelling test and whose parents completed the DCD questionnaire. Of these, 234 children also participated in the PP assessment. According to parent reports, 36% of children in third grade and 53% of children in fourth grade in the online sample had their own tablet or smartphone. In the PP sample, these percentages were 38 and 52%, respectively. These rates are in line with the results of a recent representative study about the media use by 6–13-year-olds in Germany (Feierabend et al., 2023). Table 1 contains the descriptive statistics for both (dependent) samples.

The online sample is approximately equally distributed in terms of sex and grade level (see Table 1). In the online sample, there was information about the mother's education for 3,009 (84%) of the cases. Of these, 1,310 mothers (43.5%) had an academic degree. This overrepresentation (around 17% of women in Germany have an academic degree) makes that the sample is not entirely representative in terms of socioeconomic status (SES). In the PP sample, 4th graders and boys are overrepresented (see Table 1). In terms of SES, there was information available for 206 children (88%). Of these, 41.7% of mothers had an academic degree. The mean non-verbal IQ of both samples is close to the average of 100 ($M = 101.4$ and $SD = 14.6$; $M = 100.6$ and $SD = 14.9$) for online and PP, respectively.

2.3 Material

2.3.1 Spelling

Spelling performance was assessed using a digitized version of the standardized *Weingarten spelling test for basic vocabulary* (WRT 3+ for 3rd graders; Birkel, 2007a; test–retest reliability $r > 0.93$, and WRT4+ for 4th graders; Birkel, 2007b, parallel-test reliability $r > 0.94$). The same items were used in the digitalized version as in the PP version. A strong correlation between the results on the digitalized and the PP test was reported (WRT 3+: $r = 0.74$, $n = 68$, WRT 4+: $r = 0.86$, $n = 165$, Rothe et al., 2022) but the correlation values were slightly lower than those for the test–retest reliability of the original PP test. After a sentence frame with a target word was spoken aloud to the children, they were are asked to insert the target words without a time

TABLE 1 Descriptive statistics [*n* (%)] for the online and PP samples.

		Online (*N* = 3,453)	PP (*N* = 225)
State	Bavaria	2,708 (78.4%)	72 (32.0%)
	Hesse	745 (21.6%)	153 (68.0%)
Grade *	3	1,590 (46.0%)	62 (27.6%)
	4	1,863 (54.0%)	163 (72.4%)
Sex	girl	1,694 (49.1%)	99 (44.0%)
	boy	1,759 (50.9%)	126 (56.0%)
Age	*M* (*SD*)	9;9 (0;7)	10;0 (0;7)
	range	8;1–11;8	8;8–11;8
Low fine motor skills		290 (8.4%)	32 (14.2%)
Non-verbal IQ	*M* (*SD*)	101.4 (14.6)	100.6 (14.9)
	range	50–153	64–135
Days between the tests	*M* (*SD*)	N/A	100 (61)
	range	N/A	19–237

PP, Paper-Pencil; *grade at the moment of the online assessment; **intelligence data were available for *N* = 3,202 and 211, respectively, and based on own norms applied to the CFT 20-R (Weiß, 2006); N/A, not applicable; cut-off for low fine motor skills was $z < -1.25$.

limit (3rd grade: 55 words, 4th grade: 60 words). In the online assessment, children wrote using the in-screen keyboard of the device. The number of correctly spelled words was scored. For the online sample, standardized values were obtained using grade-specific norms based on the complete sample that had used the web-based application. For more information about the norm development, we refer to Visser et al. (2020). Grade-specific norms from the PP-version of the test (Birkel, 2007a, 2007b) were used for obtaining standardized scores for the spelling performance in the PP sample.

2.3.2 DCD-questionnaire (DCD-Q)

Fine motor skills were assessed using the German translation of the parental DCD-Questionnaire (DCD-Q; Kennedy-Behr et al., 2013). This parent-report screening instrument has originally developed for screening for symptoms of coordination disorders in children, aged 5–15 years. It contains 15 items assessing gross motor skills (6 items; Cronbach's alpha = 0.83), fine motor skills (4 items, Cronbach's alpha = 0.86), and general coordination (5 items, Cronbach's alpha = 0.65). The reliability (internal consistency Cronbach's alpha = 0.88) and validity (correlation with the Movement Assessment Battery $r = -0.59$, $p < 0.001$) of the original English version have been supported (Wilson et al., 2000). Note, this parental questionnaire is a screening tool and it is not possible to determine a DCD diagnosis based on its results. However, a recent meta-analysis revealed good sensitivity (0.87) and specificity (0.83) of the DCD-Q for a DCD-classification based on the Diagnostic and Statistical Manual of Mental Disorder (DSM; Park and Kim, 2024). The DCD-Q captures the fine motor skills by asking the parents (1) Your child's printing or writing or drawing in class is fast enough to keep up with the rest of the children in the class, (2) Your child's printing or writing letters, numbers and words is legible, precise and accurate, (3) Your child uses appropriate effort or tension when printing or writing or drawing (no excessive pressure or tightness of grasp on the pencil, writing is not too heavy or dark, or too light) and (4) Your child cuts out pictures and shapes accurately and easily. Questions 1–3 cover the most relevant aspects of graphomotor skills (speed/fluency, accuracy/legibility and pressure). For the analyses, we only used the scores on fine motor skills, for which *z*-scores were obtained based on the complete sample that had used the web-based application. Low fine motor skills were defined by *z*-scores < −1.25 on the fine motor scale, which corresponds to the scoring advised in the questionnaire's manual, indicating clinical relevance.

2.3.3 Reading

A digitized version of the standardized *Wuerzburger Silent Reading Test – Revised* (Schneider, 2011) was used to measure reading fluency. The relation between results on the digitalized and the PP test was reported to be strong ($r = 0.80$, $n = 233$, Rothe et al., 2022) and was similar to the test–retest reliability of the original PP test ($r = 0.80$–0.82). Children were presented with a series of written words and asked to select the corresponding picture among four options within 5 min. Standardized values were obtained using grade-specific norms based on the complete sample that had used the web-based application. For more information about the norm development, we refer to Visser et al. (2020).

2.4 Statistical analysis

We applied linear and non-linear models to evaluate the effect of fine motor skills on the spelling performance in the online assessment. Generalized additive models (GAM) can be used to determine complex non-linear regression effects (Hastie et al., 2009) by automatically determining the optimal combination of non-linear basis functions (Wood et al., 2017). To model spelling accuracy as (potentially) non-linear function of fine motor skills and test for interactions with the child's sex and tablet or smartphone ownership (ToS), we implemented a GAM with the following form:

$$g(\text{outcome}) = \alpha + \beta X + f1(\text{fine motor}) + f2(\text{fine motor}, by = \text{sex}) + f3(\text{fine motor}, by = \text{ToS})$$

where α is the intercept, β is the vector of parameters associated with the set of explanatory variables X (sex and ToS), *fx* are the smooth

TABLE 2 Coefficients of the GLM and GAM predicting spelling.

GLM Spelling	Estimate	SE	*t*	*p*
(Intercept)	50.67	0.25	199.64	< 0.001
Female sex (reference: male)	−0.56	0.32	−1.71	0.09
ToS (reference: no ToS)	−1.09	0.31	−3.53	< 0.001
Fine motor skills	3.56	0.30	12.04	< 0.001
Fine motor skills * sex	1.23	0.39	3.16	< 0.01
Fine motor skills * ToS	−0.83	0.37	−2.24	0.03
GAM Spelling	**Estimate**	**SE**	***t***	***p***
(Intercept)	51.07	0.26	197.506	< 0.001
Female sex (reference: male)	−0.45	0.32	−1.40	.16
ToS (reference: no ToS)	−1.19	0.31	−3.86	< 0.001
Smooth terms	**edf**	**Ref.df**	***F***	***p***
s(Fine motor skills)	2.93	3.64	40.29	< 0.001
s(Fine motor skills):male	< 0.01	< 0.001	0.04	0.99
s(Fine motor skills):female	1.00	1.00	9.10	< 0.01
s(Fine motor skills):no ToS	< 0.01	< 0.01	< 0.01	0.99
s(Fine motor skills):ToS	1.02	1.04	4.41	0.03

ToS, Tablet or smartphone.

functions and *by* defines the interaction terms of the smooth functions. The smooth functions are associated with estimated degrees of freedom (EDF) indicating a linear (EDF = 1) or non-linear (EDF > 1) relation with the related *p*-value, indicating the extent to which the shape and direction of the effect is certain. In addition to the GAM we applied a generalized linear model (GLM) with the same explanatory variables and interaction terms as in the GAM.

We used the Akaike Information Criterion (AIC) to compare the model performance of the linear and non-linear model (lower scores indicate better model performance). The mgcv package (Wood and Wood, 2015) in RStudio 2022.07.2 (R 4.1.2) was used to apply the GAM and GLM.

To evaluate whether children with low fine motor skills achieve better spelling performance (dependent variable) in the online compared to the PP assessment (mode effect as within-subject factor) and whether this mode effect is the same in children with low and at least fine motor skills (between-subject factor), we applied a mixed ANOVA. Since all participants first took the online test and then the PP test, we expected the raw scores of the PP test to be higher than those of the online test for all participants due to test repetition effects, but children with low fine motor skills would show a lower raw score difference between online and PP testing than children with typical fine motor development. We included the child's sex and ToS in the model (between-subject factors) to examine interaction effects with fine motor skills.

To evaluate whether fine motor skills affect the school grade in German above and beyond the spelling performance, we applied path analysis in MPlus (Muthén and Muthén, 2011). More specifically, we evaluated if there was a direct effect of fine motor skills on the school grade in German on top of indirect effects via the spelling and reading performance in the online assessment, including the interaction between sex and fine motor skills. The alpha level was set at 0.01 for all analyses.

We excluded participants with fine motor z-scores more than 1.5 times the interquartile range below the 1st quartile (Q_1–1.5*IQR = −2.46) as the parental screening of motor difficulties (DCD-Q) is not suitable to discriminate in the lowest range (Pannekoek et al., 2012; Wilson et al., 2009). Note, there were no participants with fine motor skills more than 1.5 times the interquartile range above the 3th quartile. This resulted in a final sample of 3,453 children in the online assessment and 225 children in the PP assessment. The descriptive statistics for these samples are shown in Table 1.

3 Results

3.1 Linear and non-linear relation between spelling and fine motor skills

The mean *t*-value for spelling in the online sample was 50.2 (*SD* = 9.6). All coefficients of the GLM and GAM are shown in Table 2. The linear model revealed a positive relation between spelling and fine motor skills which additionally interacts with sex. Girls reach lower spelling scores than boys when fine motor skills are below average but there is no difference between spelling scores of girls and boys when fine motor skills are at least average. Overall there is no significant difference between spelling scores of girls and boys (girls: *M* = 51.1, *SD* = 9.4; boys: *M* = 49.8, *SD* = 9.6). There is no significant interaction with ToS, but overall, children with their own tablet or smartphone reach lower spelling skills than children without (with ToS: *M* = 51.0, *SD* = 9.5; without ToS: *M* = 49.8, *SD* = 9.5). Modeling non-linear regression effects with the same predictors revealed a non-linear relation between spelling and fine motor skills (indicated by the significant edf of 2.93) and confirmed the interaction with sex and non-interaction with ToS. Like in the linear model, girls reach lower

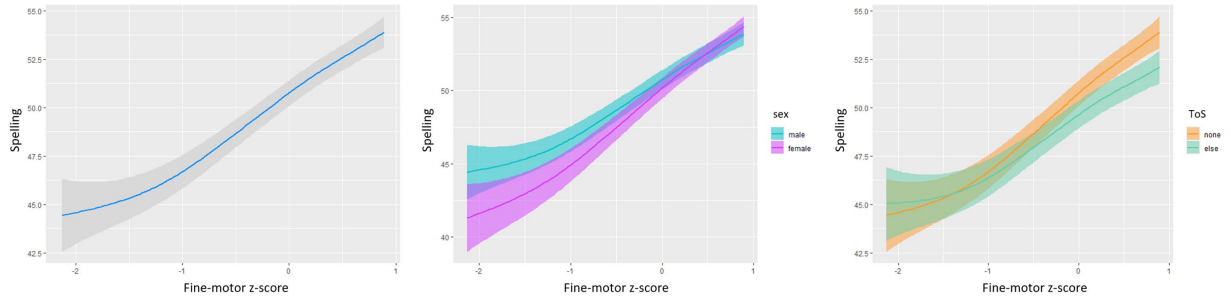

FIGURE 1
Estimated curves (shading 95%-level confidence region) for the non-linear relation between spelling and fine motor skills with sex and ToS considered.

TABLE 3 Spelling scores of the online and PP sample for children with below average and at least average fine motor skills.

	Spelling t-score, M (SD)		
	Online sample (N = 3,453)	PP sample (N = 225)	
	Online assessment	Online assessment	PP assessment
Fine motor skills			
At least average (z-scores ≥ −1.25)	51.0 (9.3)	48.4 (9.7)	52.9 (9.8)
Below average (z-scores < −1.25)	44.6 (9.6)	43.2 (10.1)	48.0 (8.9)
Total sample	50.5 (9.5)	47.7 (9.9)	52.2 (9.8)

spelling scores than boys when fine motor skills are below average, but this sex difference disappears when fine motor skills are at least average. The edf of 1 for the smooth-term of girls in contrast to the edf < 0.01 for the smooth-term of boys indicate that, in the relation between spelling and fine motor skills, sex interacts in a linear way. A comparison of the AIC of the GLM (24972.62) and GAM (24971.34) demonstrates that both models performed almost equally well, which is confirmed by the results of a chi-square test comparing the GLM and GAM ($p = 0.11$). The estimated curves for the non-linear relation between spelling and fine motor skills with interactions of sex and ToS are shown in Figure 1.

3.2 Mode effect in children with low fine motor skills

The mixed ANOVA revealed main effects for test mode ($F_{(1, 219)} = 48.44$, $p < 0.001$, $\eta^2 = 0.18$) and fine motor skills ($F_{(1, 219)} = 8.47$, $p = 0.004$, $\eta^2 = 0.04$) with higher scores in the PP assessment compared to the online assessment and lower scores in children with low fine motor skills compared to children with at least average fine motor skills (means and standard deviations are displayed in Table 3). The hypothesized interaction between test mode and fine motor skills was not evidenced by the present data ($F_{(1, 219)} = 0.003$, $p = 0.96$, $\eta^2 < 0.01$). The interaction between test mode and ToS ($F_{(1, 219)} = 4.68$, $p = 0.03$, $\eta^2 = 0.02$) does not reach significance. As hypothesized, there was no interaction between test mode and sex ($F_{(1, 219)} = 0.21$, $p = 0.65$, $\eta^2 < 0.01$). Visualizations of the interactions (i) test mode * fine motor skills and (ii) test mode * ToS are shown in Figure 2.

3.3 Effects of fine motor skills on school grade in the subject German

Due to missing data on the reading assessment, this analysis was based on a sample of $N = 3.453$. The mean t-value for reading in the online sample was 50.5 ($SD = 9.6$). Figure 3 shows the mediation model that was evaluated. The chi square test was significant: $\chi^2(3) = 9.82$, $p = 0.02$, which could be due to its sensitivity to large sample sizes (Sass, 2011). The fit indices showed a good model fit: CFI = 0.997, TLI = 0.989, SRMR = 0.011, RMSEA = 0.026 (90% CI = 0.009–0.044). Fine motor skills appear to be a significant predictor of school grade in the subject German ($\beta = -0.215$, $p < 0.001$). This relation is partially mediated by reading ($\beta = -0.057$, $p < 0.001$) and spelling ($\beta = -0.079$, $p < 0.001$). Sex is no significant predictor of reading, spelling, and school grade in the subject German, while the interaction of sex and fine motor skills predicts reading ($\beta = -1.056$, $p < 0.001$) and spelling ($\beta = -1.056$, $p < 0.001$), but not the school grade in the subject German ($\beta = 0.061$, $p = 0.022$).

4 Discussion

The present study investigated effects of fine motor skills on spelling performance. First, the results did not confirm the hypothesized weaker relation between fine motor skills and spelling performance for children with low fine motor skills than for children with at least average fine motor skills. Instead, the results showed a rather linear relation between fine motor skills and spelling with an interaction effect for sex. More specifically, spelling skills appeared

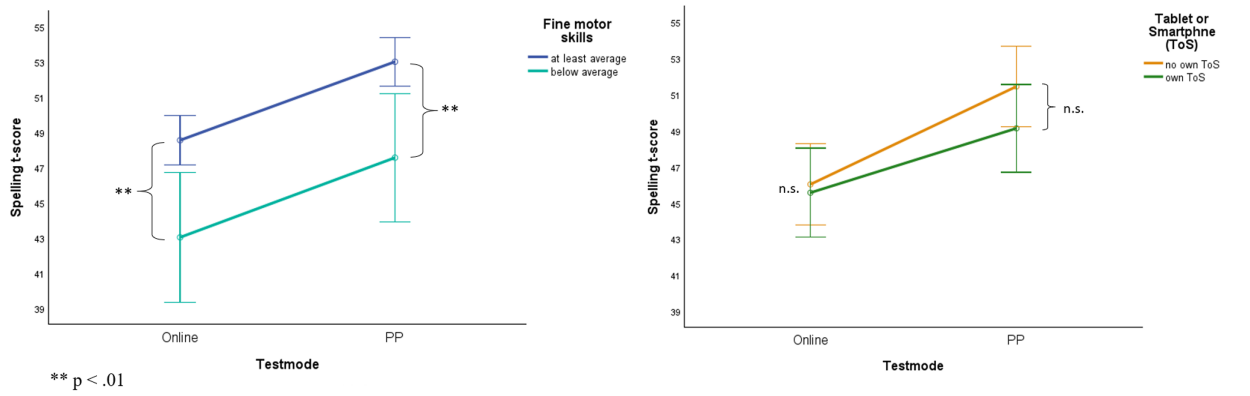

FIGURE 2
Main and interaction effects of Testmode, fine motor skills, and ToS.

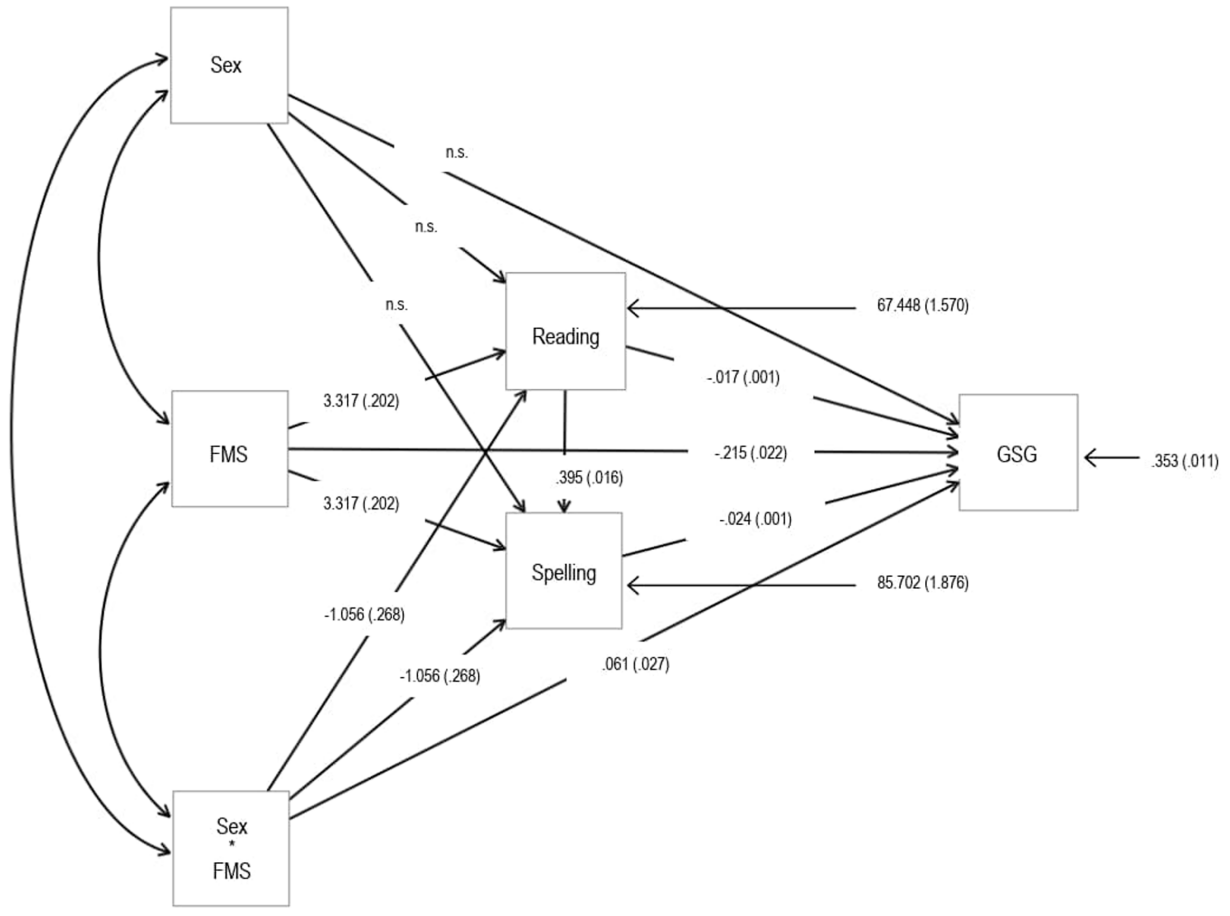

FIGURE 3
Mediation model with reading and spelling as mediator in the relation between fine motor skills (FMS) and grade for the subject German (GSG).

lower in girls than boys only in case of low levels of fine motor skills. Second, with respect to test mode, the results supported neither our hypothesis that children with low fine motor skills achieve better spelling performance when they write with a keyboard instead of on paper, nor the expected interaction between test mode and having an own tablet or smartphone in the effect on spelling achievement. As expected, the test mode effect was not moderated by sex either. Third, the results confirmed the hypothesis that fine motor skills affect the school grade in the subject German above and beyond the spelling and reading performance.

The absence of different test mode effects in children with below average fine motor skills compared to children with at least average

fine motor skills is against our hypothesis. The hypothesis stated that in children with low fine motor skills, the motor effort and therefore load on working memory is higher for handwriting than for typing, leading to better spelling performance when writing with a keyboard. That we still find the same test mode effects for children with below and at least average fine motor skills may indicate, on the one side, that the motor effort involved in handwriting and typing is comparable and, on the other hand, that other cognitive functions underlie both tasks. Other underlying cognitive functions such as working memory may also correspond with the finding of a linear relation between fine motor skills and spelling performance instead of the hypothesized non-linear relation. Another possible explanation is that fine motor skills may affect the acquisition of spelling per se, so that the spelling deficits are also evident in typing, even if motor effort is lower in typing. An automatization deficit in graphomotor skills could be an explanation for an affected spelling acquisition. If handwriting is not automated (in beginning writers or children with fine motor difficulties), the child needs increased effort for planning and performing the movement of writing and there is less working memory space left for other tasks. Speculatively, the automatization deficit may not only impair the recall of stored orthographic knowledge during writing, but also memorisation of orthographic knowledge already during the writing process (e.g., copy writing). Assuming that children with developmental dyslexia also have some automatizations deficits, among others, our results and speculation about the relation of the automatization deficit and memorisation seem consistent with results of a previous study, which found no differences in the mode effects on spelling in children with developmental dyslexia compared to children with typical development (Jung et al., 2021).

However, the results of the present study already show that the spelling performance of children with low fine motor skills cannot simply be improved by switching from handwriting to keyboarding. Rather, children with low fine motor skills should receive training in handwriting automatization. In addition, orthographic learning can be expanded through tasks that do not involve motor skills (e.g., error identification and orthographic choice).

Numerous studies investigated the effects of different types of keyboarding instructions (e.g., touch-typing) on typing skills (e.g., Donica et al., 2018), spelling, and other writing-related skills such as narrative-writing (e.g., Van Weerdenburg et al., 2019). In terms of test mode effects, however, familiarity with the device is of particular interest. In the present study, test mode effects did not depend on children having their own ToS or not, which was unexpected. Particularly surprising is that children who do not have their own ToS show better spelling skills in the online assessment compared to children with own ToS. Together, this indicates that device-familiarity does not advance spelling performance in the online assessment, but it contrasts with previous results from computer-based math (Bennett et al., 2008) and reading (Odo, 2012) tests.

There is a large body of evidence that girls outperform boys in fine motor task, particularly in pre- and primary school (e.g., Kokštejn et al., 2017; Matarma et al., 2020; Morley et al., 2015; Venetsanou and Kambas, 2010). Boys appear to be almost five times more likely to have severe handwriting problems than girls (Vlachos and Bonoti, 2006). In addition, girls appear to outperform boys in spelling (Adams and Simmons, 2019; Allred, 1990; Berninger and Fuller, 1992; Cordeiro et al., 2018; Petersen, 2018), but we are not aware of studies that have examined the role of sex in the relation between fine motor skills and spelling. Therefore, the present study provides new insights into this interaction by showing that below-average fine motor skills have a greater adverse effect on spelling performance in girls than in boys. Although there are some studies reporting sex differences in language lateralization (for an overview see Wallentin, 2009), which might also be associated with motor abilities (e.g., corpus callosum motor fibers; Grohs et al., 2018), research to date does not clearly suggest that sex differences in hemispheric asymmetry and cognitive performance are correlated (for a further overview see Hirnstein et al., 2019). However, the developmental perspective of this relation has not yet been investigated sufficiently. Regardless of the insufficient understanding of the underlying mechanisms, the role of sex differences should be considered both in research and in practice.

Finally, the results of the present study indicate that the effect of fine motor skills on school grades given in the subject German is, as hypothesized, only partly mediated by reading and spelling performance. Fine motor skills thus affect the school grades in the subject German above and beyond the spelling and reading performance. This raises the question about the underlying mechanism in the relation between fine motor skills and the school grade in the subject German. On the one hand, the remaining effect of fine motor skills on school grades in the subject German might be driven by a general automatization capability. On the other hand, the contribution of fine motor skills to reading and spelling performance might also be mediated by executive functions, as recent research indicates (Khoury-Metanis and Khateb, 2023; Lê et al., 2021). In addition, Michel et al. (2018) found indications that automatization deficits in motor skills might be compensated during interference control, which might also explain the full mediation by executive functions in children in the first stages of reading and spelling acquisition when handwriting is not automated, as reported by Khoury-Metanis and Khateb (2023). Altogether, these results show that low fine motor skills and its effect on reading and writing is influenced by various factors in addition to a possible automatization deficit, as reflected in the multiple deficit framework (Pennington, 2006). Future studies should investigate the role of the interaction between automatization and interference on written language acquisition in order to draw concrete conclusions for preventive measures and early interventions.

Some methodological limitations must be considered when interpreting the results of the study presented. A key limitation is that, in the sub-sample used to examine the test mode effects, all children completed the two test formats in the same order (the online assessment before the PP test). Repetition effects on the difference in performance between the two test formats could therefore not be controlled. Seifert and Paleczek (2022) showed that the test mode effect is larger when testing in the digital mode first (as in the present study) followed by the PP mode, compared to vice versa. A possible interaction of test order and fine motor skills on spelling performance should therefore be examined in a counterbalanced design. A further limitation is that motor skills were solely captured by parent ratings and based on only four items. The DCD-Q is the most widely used and researched questionnaire for parent ratings of child's motor skills with good reliability and validity (Caravale et al., 2014; Kennedy-Behr et al., 2013; Martini et al., 2011; Ray-Kaeser et al., 2019; Wilson et al., 2000, 2009).

Although many studies find high correspondence between parent ratings and performance-based assessments of motor skills (Brown and Lane, 2014; Kennedy et al., 2012; Wilson et al., 2000), some do not (Lalor et al., 2016; Schoemaker et al., 2006). Even though parents are not the most qualified people to evaluate graphomotor skills, they receive a qualified evaluation of their children's graphomotor skills through the handwriting grades given by teachers. A third limitation is the missing direct measure of device familiarity, as the present study merely captured whether the children had their own ToS. Children without their own ToS could be familiar with the device to the same extent as children with their own ToS. The present study merely captured whether the children had their own ToS, which is not a direct measure of familiarity. However, recent representative data of children in Germany indicate a relation between smartphone or tablet ownership by children and their typing skills (Feierabend et al., 2023). In addition, other factors, such as the family's socioeconomic status, could have played a role and should therefore be controlled for in future studies. Therefore, in addition to the counterbalanced design, a replication of the current study should include a direct measure of motor skills using a standardized motor test carried out by a physiotherapist or occupational therapist as well as a direct measure of device familiarity.

5 Conclusion

In conclusion, the results of the present study are consistent with other findings that emphasize the importance of fine motor skills in explaining differences in spelling performance, particularly in girls and during spelling acquisition (Danna et al., 2022; Khng and Ng, 2021; Khoury-Metanis and Khateb, 2023; Michel et al., 2019; Mohamed and O'Brien, 2022; Pritchard et al., 2021; Roebers and Jäger, 2014). Moreover, the present results demonstrate that switching from PP to digital testing does not seem to bring immediate improvement for primary school children with low fine motor skills. However, the digital mode is not a disadvantage for children with low fine motor skills either. It could therefore still be applied, because of the clear advantages in terms of time efficiency for teachers and objectivity. Based on our results fine motor difficulties should be recognized and treated before or at the beginning of spelling acquisition and particular attention should be given to girls with low fine motor skills. Further research is needed to better understand the role of underlying cognitive functions (e.g., working memory) and the causal chain of motor development and literacy.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by the ethics committees of the University Hospital of the Ludwig-Maximilians-University Munich and the DIPF | Leibniz Institute for Research and Information in Education, Frankfurt am Main. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation in this study was provided by the participants' legal guardians/next of kin.

Author contributions

JR: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Writing – original draft. GS-K: Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing – review & editing. MH: Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing – review & editing. LV: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Writing – original draft.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. This study was supported by a grant from the German Federal Ministry of Education and Research (BMBF) (grant nos. 01GJ1601A and 01GJ1601B).

Acknowledgments

We thank the children and their families for participating in the current study and Meister Cody GmbH for their role in developing the online assessment. In addition, we thank Katharina Grunwald, Janosch Linkersdoerfer (DIPF), Julia Kalmar, Ruth Görgen und Stefan Haberstroh (LMU) for their support in data collection and data preparation.

Conflict of interest

The 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.

Publisher's note

References

Adams, A.-M., and Simmons, F. R. (2019). Exploring individual and gender differences in early writing performance. *Read. Writ.* 32, 235–263. doi: 10.1007/s11145-018-9859-0

Adams, A.-M., Simmons, F., and Willis, C. (2015). Exploring relationships between working memory and writing: individual differences associated with gender. *Learn. Individ. Differ.* 40, 101–107. doi: 10.1016/j.lindif.2015.04.011

Allred, R. A. (1990). Gender differences in spelling achievement in grades 1 through 6. *J. Educ. Res.* 83, 187–193. doi: 10.1080/00220671.1990.10885955

Beers, S. F., Berninger, V., Mickail, T., and Abbott, R. (2018). Online writing processes in translating cognition into language and transcribing written language by stylus and keyboard in upper elementary and middle school students with persisting dysgraphia or dyslexia. *Learning Disabilities* 23. doi: 10.18666/LDMJ-2018-V23-I2-9008

Bennett, R. E., Braswell, J., Oranje, A., Sandene, B., Kaplan, B., and Yan, F. (2008). Does it matter if I take my mathematics test on computer? A second empirical study of mode effects in NAEP. *J. Technol. Learning Assessment* 6:n9.

Berninger, V. W., and Fuller, F. (1992). Gender differences in orthographic, verbal, and compositional fluency: implications for assessing writing disabilities in primary grade children. *J. Sch. Psychol.* 30, 363–382. doi: 10.1016/0022-4405(92)90004-O

Birkel, P. (2007a). WRT 3+ Weingartener Grundwortschatz Recht-schreib-Test für dritte und vierte Klassen. Boston, MA: Hogrefe.

Birkel, P. (2007b). WRT 4+ Weingartener Grundwortschatz Rechtschreib-Test für vierte und fünfte Klassen. Boston, MA: Hogrefe.

Brown, T., and Lane, H. (2014). Comparing a parent-report and a performance-based measure of children's motor skill abilities: are they associated? *Occup. Ther. Health Care* 28, 371–381. doi: 10.3109/07380577.2014.933381

Caramia, S., Gill, A., Ohl, A., and Schelly, D. (2020). Fine motor activities in elementary school children: a replication study. *Am. J. Occup. Ther.* 74, 7402345010p1–7402345010p7. doi: 10.5014/ajot.2020.035014

Caravale, B., Baldi, S., Gasparini, C., and Wilson, B. N. (2014). Cross-cultural adaptation, reliability and predictive validity of the Italian version of developmental coordination disorder questionnaire (DCDQ). *Eur. J. Paediatr. Neurol.* 18, 267–272. doi: 10.1016/j.ejpn.2013.11.009

Cerni, T., and Job, R. (2024). Spelling processing during handwriting and typing and the role of reading and visual-motor skills when typing is less practiced than handwriting. *Read. Writ.* 37, 205–237. doi: 10.1007/s11145-023-10418-2

Clinton, V. (2019). Reading from paper compared to screens: a systematic review and meta-analysis. *J. Res. Read.* 42, 288–325. doi: 10.1111/1467-9817.12269

Cordeiro, C., Castro, S. L., and Limpo, T. (2018). Examining potential sources of gender differences in writing: the role of handwriting fluency and self-efficacy beliefs. *Writ. Commun.* 35, 448–473. doi: 10.1177/0741088318788843

Cummine, J., Chouinard, B., Szepesvari, E., and Georgiou, G. K. (2015). An examination of the rapid automatized naming–reading relationship using functional magnetic resonance imaging. *Neuroscience* 305, 49–66. doi: 10.1016/j.neuroscience.2015.07.071

Danna, J., Longcamp, M., Nalborczyk, L., Velay, J.-L., Commengé, C., and Jover, M. (2022). Interaction between orthographic and graphomotor constraints in learning to write. *Learn. Instr.* 80:101622. doi: 10.1016/j.learninstruc.2022.101622

Delgado, P., Vargas, C., Ackerman, R., and Salmerón, L. (2018). Don't throw away your printed books: a meta-analysis on the effects of reading media on reading comprehension. *Educ. Res. Rev.* 25, 23–38. doi: 10.1016/j.edurev.2018.09.003

Donica, D. K., Giroux, P., and Faust, A. (2018). Keyboarding instruction: comparison of techniques for improved keyboarding skills in elementary students. *J. Occup. Ther. Sch. Early Interv.* 11, 396–410. doi: 10.1080/19411243.2018.1512067

Downing, C., and Caravolas, M. (2023). Handwriting legibility and fluency and their patterns of concurrent relations with spelling, graphomotor, and selective attention skills. *J. Exp. Child Psychol.* 236:105756. doi: 10.1016/j.jecp.2023.105756

Eickelmann, B., Bos, W., Gerick, J., Goldhammer, F., Schaumburg, H., Schwippert, K., et al. (2019). ICILS 2018# Deutschland: Computer-und informationsbezogene Kompetenzen von Schülerinnen und Schülern im zweiten internationalen Vergleich und Kompetenzen im Bereich Computational Thinking. Munich: Waxmann Verlag.

Elliott, L. J., Ljubijanac, M., and Wieczorek, D. (2020). "The effect of screen size on Reading speed: a comparison of three screens to print" in Advances in human factors in training, education, and learning sciences: Proceedings of the AHFE 2019 international conference on human factors in training, education, and learning scienc. eds. W. Karwowski, T. Ahram and S. Nazir (Cham: Springer International Publishing), 103–109.

Feierabend, S., Rathgeb, T., Kheredmand, H., and Glöckler, S. (2023). KIM-Studie 2022-Kindheit, Internet, Medien: Basisuntersuchung zum Medienumgang 6-bis 13-Jähriger. Medienpädagogischer Forschungsverbund Südwest, vol. *14*. Stuttgart: Medienpädagogischer Forschungsverbund Südwest (mpfs).

Feng, L., Lindner, A., Ji, X. R., and Malatesha Joshi, R. (2019). The roles of handwriting and keyboarding in writing: a meta-analytic review. *Read. Writ.* 32, 33–63. doi: 10.1007/s11145-017-9749-x

Goldhammer, F., Harrison, S., Bürger, S., Kröhne, U., Lüdtke, O., Robitzsch, A., et al. (2018). Vertiefende Analysen zur Umstellung des Modus von Papier auf Computer. *PISA* 2019, 163–186.

Grohs, M. N., Reynolds, J. E., Dewey, D., and Lebel, C. (2018). Corpus callosum microstructure is associated with motor function in preschool children. *NeuroImage* 183, 828–835. doi: 10.1016/j.neuroimage.2018.09.004

Hastie, T., Tibshirani, R., and Friedman, J. (2009). *The elements of statistical learning: prediction, inference and data mining*. New York: Springer-Verlag.

He, J. L., Fuelscher, I., Coxon, J., Barhoun, P., Parmar, D., Enticott, P. G., et al. (2018). Impaired motor inhibition in developmental coordination disorder. *Brain Cogn.* 127, 23–33. doi: 10.1016/j.bandc.2018.09.002

Hirnstein, M., Hugdahl, K., and Hausmann, M. (2019). Cognitive sex differences and hemispheric asymmetry: a critical review of 40 years of research. *Laterality Asymmetries Body Brain Cognit.* 24, 204–252. doi: 10.1080/1357650X.2018.1497044

Horkay, N., Bennett, R. E., Allen, N., Kaplan, B., and Yan, F. (2006). Does it matter if I take my writing test on computer? An empirical study of mode effects in NAEP. *J. Technol. Learn. Assessment* 5:n2.

Johnson, S. (2012). A clinical handbook on child development Paediatrics—E-book. Amsterdam: Elsevier Health Sciences.

Jung, S., Moeller, K., Klein, E., and Heller, J. (2021). Mode effect: an issue of perspective? Writing mode differences in a spelling assessment in German children with and without developmental dyslexia. *Dyslexia* 27, 373–410. doi: 10.1002/dys.1675

Kennedy, J., Brown, T., and Chien, C.-W. (2012). Motor skill assessment of children: is there an association between performance-based, child-report, and parent-report measures of children's motor skills? *Phys. Occup. Ther. Pediatr.* 32, 196–209. doi: 10.3109/01942638.2011.631101

Kennedy-Behr, A., Wilson, B. N., Rodger, S., and Mickan, S. (2013). Cross-cultural adaptation of the developmental coordination disorder questionnaire 2007 for German-speaking countries: DCDQ-G. *Neuropediatrics* 44, 245–251. doi: 10.1055/s-0033-1347936

Khng, K.-H., and Ng, E.-L. (2021). Fine motor and executive functioning skills predict maths and spelling skills at the start of kindergarten: a compensatory account (La motricidad fina y las funciones ejecutivas predicen las competencias en matemáticas y Lengua escrita al comienzo de la etapa preescolar: Una propuesta compensatoria). *J. Study Educ. Dev.* 44, 675–718. doi: 10.1080/02103702.2021.1897232

Khoury-Metanis, A., and Khateb, A. (2023). Executive functions mediate fine motor skills' contribution to literacy achievement: a longitudinal study of Arabic-speaking children. *Read. Writ.* 37, 1–25.

KMK – Kultusministerkonferenz (2022). Bildungsstandards für das Fach Deutsch Primarbereich. Available at: https://www.kmk.org/fileadmin/veroeffentlichungen_beschluesse/2022/2022_06_23-Bista-Primarbereich-Deutsch.pdf (accessed June 23, 2022).

Kokštejn, J., Musálek, M., and Tufano, J. J. (2017). Are sex differences in fundamental motor skills uniform throughout the entire preschool period? *PLoS One* 12:e0176556. doi: 10.1371/journal.pone.0176556

Kong, Y., Seo, Y. S., and Zhai, L. (2018). Comparison of reading performance on screen and on paper: a meta-analysis. *Comput. Educ.* 123, 138–149. doi: 10.1016/j.compedu.2018.05.005

Lachambre, C., Proteau-Lemieux, M., Lepage, J.-F., Bussières, E.-L., and Lippé, S. (2021). Attentional and executive functions in children and adolescents with developmental coordination disorder and the influence of comorbid disorders: a systematic review of the literature. *PLoS One* 16:e0252043. doi: 10.1371/journal.pone.0252043

Lalanne, C., Falissard, B., Golse, B., and Vaivre-Douret, L. (2012). Refining developmental coordination disorder subtyping with multivariate statistical methods. *BMC Med. Res. Methodol.* 12:107. doi: 10.1186/1471-2288-12-107

Lalor, A., Brown, T., and Murdolo, Y. (2016). Relationship between children's performance-based motor skills and child, parent, and teacher perceptions of children's motor abilities using self/informant-report questionnaires. *Aust. Occup. Ther. J.* 63, 105–116. doi: 10.1111/1440-1630.12253

Lê, M., Quémart, P., Potocki, A., Gimenes, M., Chesnet, D., and Lambert, E. (2021). Modeling the influence of motor skills on literacy in third grade: contributions of executive functions and handwriting. *PLoS One* 16:e0259016. doi: 10.1371/journal.pone.0259016

Martini, R., St-Pierre, M.-F., and Wilson, B. N. (2011). French Canadian cross-cultural adaptation of the developmental coordination disorder questionnaire'07: DCDQ-FC. *Can. J. Occup. Ther.* 78, 318–327. doi: 10.2182/cjot.2011.78.5.7

Matarma, T., Lagström, H., Löyttyniemi, E., and Koski, P. (2020). Motor skills of 5-year-old children: gender differences and activity and family correlates. *Percept. Mot. Skills* 127, 367–385. doi: 10.1177/0031512519900732

McGrath, L. M., Peterson, R. L., and Pennington, B. F. (2020). The multiple deficit model: Progress, problems, and prospects. *Sci. Stud. Read.* 24, 7–13. doi: 10.1080/10888438.2019.1706180

McHale, K., and Cermak, S. A. (1992). Fine motor activities in elementary school: preliminary findings and provisional implications for children with fine motor problems. *Am. J. Occup. Ther.* 46, 898–903. doi: 10.5014/ajot.46.10.898

Michel, E., Molitor, S., and Schneider, W. (2018). Differential changes in the development of motor coordination and executive functions in children with motor coordination impairments. *Child Neuropsychol.* 24, 20–45. doi: 10.1080/09297049.2016.1223282

Michel, E., Molitor, S., and Schneider, W. (2019). Motor coordination and executive functions as early predictors of Reading and spelling acquisition. *Dev. Neuropsychol.* 44, 282–295. doi: 10.1080/87565641.2019.1584802

Mohamed, M. B. H., and O'Brien, B. A. (2022). Defining the relationship between fine motor visual-spatial integration and reading and spelling. *Read. Writ.* 35, 877–898. doi: 10.1007/s11145-021-10165-2

Morley, D., Till, K., Ogilvie, P., and Turner, G. (2015). Influences of gender and socioeconomic status on the motor proficiency of children in the UK. *Hum. Mov. Sci.* 44, 150–156. doi: 10.1016/j.humov.2015.08.022

Muthén, L. K., and Muthén, B. O. (2011, 2011). Mplus User's guide. Los Angeles, CA: Muthén & Muthén, 447–1600.

Nicolson, R. I., and Fawcett, A. J. (1990). Automaticity: a new framework for dyslexia research? *Cognition* 35, 159–182. doi: 10.1016/0010-0277(90)90013-A

Noyes, J. M., and Garland, K. J. (2003). VDT versus paper-based text: reply to Mayes, Sims and Koonce. *Int. J. Ind. Ergon.* 31, 411–423. doi: 10.1016/S0169-8141(03)00027-1

Odo, D. M. (2012). Computer familiarity and test performance on a computer-based cloze ESL reading assessment. *Teach. English Technol.* 12, 18–35.

Pannekoek, L., Rigoli, D., Piek, J. P., Barrett, N. C., and Schoemaker, M. (2012). The revised DCDQ: is it a suitable screening measure for motor difficulties in adolescents? *APAQ* 29, 81–97. doi: 10.1123/apaq.29.1.81

Park, S.-H., and Kim, E. Y. (2024). Predictive validity of the developmental coordination disorder questionnaire as a screening tool to identify motor skill problems: a systematic review and meta-analysis. *Res. Dev. Disabil.* 150:104748. doi: 10.1016/j.ridd.2024.104748

Pennington, B. F. (2006). From single to multiple deficit models of developmental disorders. *Cognition* 101, 385–413. doi: 10.1016/j.cognition.2006.04.008

Petersen, J. (2018). Gender difference in verbal performance: a meta-analysis of United States state performance assessments. *Educ. Psychol. Rev.* 30, 1269–1281. doi: 10.1007/s10648-018-9450-x

Pontart, V., Bidet-Ildei, C., Lambert, E., Morisset, P., Flouret, L., and Alamargot, D. (2013). Influence of handwriting skills during spelling in primary and lower secondary grades. *Front. Psychol.* 4:818. doi: 10.3389/fpsyg.2013.00818

Preminger, F., Weiss, P. L., and Weintraub, N. (2004). Predicting occupational performance: handwriting versus keyboarding. *Am. J. Occup. Ther.* 58, 193–201. doi: 10.5014/ajot.58.2.193

Pritchard, V. E., Malone, S. A., and Hulme, C. (2021). Early handwriting ability predicts the growth of children's spelling, but not reading, skills. *Sci. Stud. Read.* 25, 304–318. doi: 10.1080/10888438.2020.1778705

Ray-Kaeser, S., Thommen, E., Martini, R., Jover, M., Gurtner, B., and Bertrand, A. M. (2019). Psychometric assessment of the French European developmental coordination disorder questionnaire (DCDQ-FE). *PLoS One* 14:e0217280. doi: 10.1371/journal.pone.0217280

Rodrigues, P. C., Ribeiro, M., Sousa, A., Lopes, S., and Barros, R. (2019). Performance on the movement assessment battery for children: A systematic review about gender differences. [Desempeño en la batería de evaluación del movimiento para niños: una revisión sistemática sobre las diferencias de género]. *RICYDE* 15, 72–87. doi: 10.5232/ricyde2019.05505

Roebers, C. M., and Jäger, K. (2014). The relative importance of fine motor skills, intelligence, and executive functions for first graders' reading and spelling skills. *Persp. Lang. Liter.* 40, 13–17.

Rothe, J., Visser, L., Görgen, R., Kalmar, J., Schulte-Körne, G., and Hasselhorn, M. (2022). Mobile first? Ein vergleich von lese-/Rechtschreibtests in traditionellem papier-und-bleistift-format versus app-format. *Z. Erzieh.* 25, 947–973. doi: 10.1007/s11618-022-01068-1

Sass, D. A. (2011). Testing measurement invariance and comparing latent factor means within a confirmatory factor analysis framework. *J. Psychoeduc. Assess.* 29, 347–363. doi: 10.1177/0734282911406661

Schneider, W. (2011). WLLP-R: Würzburger Leise Leseprobe-Revision: Ein Gruppentest für die Grundschule. Göttingen: Hogrefe.

Schoemaker, M. M., Flapper, B., Verheij, N. P., Wilson, B. N., Reinders-Messelink, H. A., and de Kloet, A. (2006). Evaluation of the developmental coordination disorder questionnaire as a screening instrument. *Dev. Med. Child Neurol.* 48, 668–673. doi: 10.1017/S001216220600140X

Schütz, C., and Schack, T. (2020). Working memory load does not affect sequential motor planning. *Acta Psychol.* 208:103091. doi: 10.1016/j.actpsy.2020.103091

Seifert, S., and Paleczek, L. (2022). Comparing tablet and print mode of a German reading comprehension test in grade 3: influence of test order, gender and language. *Int. J. Educ. Res.* 113:101948. doi: 10.1016/j.ijer.2022.101948

Stanat, P., Schipolowski, S., Schneider, R., Sachse, K. A., Weirich, S., and Henschel, S. (2022). IQB-Bildungstrend 2021: Kompetenzen in den Fächern Deutsch und Mathematik am Ende der 4. Jahrgangsstufe im dritten Ländervergleich. Munich: Waxmann Verlag.

Stich, H. L. (2009). Teilleistungsstörungen bei einschulungskindern. *Kinder- und Jugendmedizin* 9, 42–48. doi: 10.1055/s-0038-1629011

Suggate, S., Pufke, E., and Stoeger, H. (2016). The effect of fine and grapho-motor skill demands on preschoolers' decoding skill. *J. Exp. Child Psychol.* 141, 34–48. doi: 10.1016/j.jecp.2015.07.012

Van Weerdenburg, M., Tesselhof, M., and van der Meijden, H. (2019). Touch-typing for better spelling and narrative-writing skills on the computer. *J. Comput. Assist. Learn.* 35, 143–152. doi: 10.1111/jcal.12323

Venetsanou, F., and Kambas, A. (2010). Motor performance differences in preschool aged boys and girls. Preschool children: Physical activity, behavioral assessment and developmental challenges. New York, NY: Nova Science Publishers, Inc, 19–37.

Visser, L., Kalmar, J., Linkersdörfer, J., Görgen, R., Rothe, J., Hasselhorn, M., et al. (2020). Comorbidities between specific learning disorders and psychopathology in elementary school children in Germany. *Front. Psychiatr.* 11:292. doi: 10.3389/fpsyt.2020.00292

Vlachos, F., and Bonoti, F. (2006). Explaining age and sex differences in children's handwriting: a neurobiological approach. *Eur. J. Dev. Psychol.* 3, 113–123. doi: 10.1080/17405620500371455

Wallentin, M. (2009). Putative sex differences in verbal abilities and language cortex: a critical review. *Brain Lang.* 108, 175–183. doi: 10.1016/j.bandl.2008.07.001

Wang, L., and Wang, L. (2024). Relationships between motor skills and academic achievement in school-aged children and adolescents: a systematic review. *Children* 11:336. doi: 10.3390/children11030336

Weiß, R. H. (2006). Grundintelligenztest Skala 2—Revision (CFT 20-R). Göttingen: Hogrefe.

Wicki, W., Hurschler Lichtsteiner, S., Saxer Geiger, A., and Müller, M. (2014). Handwriting fluency in children. *Swiss J. Psychol.* 73, 87–96. doi: 10.1024/1421-0185/a000127

Wilson, B. N., Crawford, S. G., Green, D., Roberts, G., Aylott, A., and Kaplan, B. J. (2009). Psychometric properties of the revised developmental coordination disorder questionnaire. *Phys. Occup. Ther. Pediatr.* 29, 182–202. doi: 10.1080/01942630902784761

Wilson, B. N., Kaplan, B. J., Crawford, S. G., Campbell, A., and Dewey, D. (2000). Reliability and validity of a parent questionnaire on childhood motor skills. *Am. J. Occup. Ther.* 54, 484–493. doi: 10.5014/ajot.54.5.484

Wilson, P. H., Smits-Engelsman, B., Caeyenberghs, K., Steenbergen, B., Sugden, D., Clark, J., et al. (2017). Cognitive and neuroimaging findings in developmental coordination disorder: new insights from a systematic review of recent research. *Dev. Med. Child Neurol.* 59, 1117–1129. doi: 10.1111/dmcn.13530

Wood, S., and Wood, M. S. (2015). Package 'mgcv'. *R package version*, 1:729.

Wood, S., Scheipl, F., and Wood, M. S. (2017). Package 'gamm4'. *Am Stat*, 45, 0–2.