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Variability in the effects of bilingualism on task switching of cognitively healthy and cognitively impaired older bilinguals

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Introduction: The impact of bilingualism on executive function has been extensively discussed, but inconsistent evidence has been reported. These discrepancies may stem from the complexities of being bilingual and the various ways of measuring bilingual experiences. This study aims to clarify the debate by providing a systematic critique and analysis on how different measurements of bilingualism can lead to different results within the same group of bilinguals.

Methods: We tested 48 cognitively healthy (CH) and 43 cognitively impaired (CI) older adults (M_{age} = 73.25 and 79.72 years, respectively) using the color-shape switching task. We assessed bilingualism using six different methods based on dominant language usage: five categorical computations and one continuous measurement.

Results and discussion: The results varied depending on the method of measuring bilingualism and the participant group. For CH older adults, a significant effect of bilingualism on cognition performance was observed only when using the categorical variable based on a cutoff of 70% dominant language usage, but not with other categorical computations or the continuous approach. For CI older adults, no effect of bilingualism was found, regardless of the type of measurement used. In summary, our results demonstrated that different measurements of language use can yield different results within the same group of bilinguals using a single task. Our study yielded important implications for bilingual research: the findings challenge the current methodologies used to describe bilingual experiences and call for care and consideration of context and the complexity when examining the effects of bilingual experience on executive functions.

KEYWORDS

bilingualism, language usage, executive function, task switching, normal aging, dementia

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Introduction

Bilingualism has gained enormous attention over the past few decades due to the purported bilingual advantage in executive functions (EF). To manage two languages, bilinguals need to rely on the language control mechanism that is related to executive function—a set of general cognitive control processes that include inhibitory control, working memory updating and monitoring, mental set shifting, etc. (e.g., Miyake et al., 2000). According to the adaptive control hypothesis (Green and Abutalebi, 2013), the amount of executive control required from a bilingual is the most extensive in the dual-language context, where two languages are spoken in one environment. Thus, it has been argued that bilinguals have better EF than monolinguals due to the daily practice of using two languages (e.g., Bialystok et al., 2008; Costa et al., 2008; Prior and MacWhinney, 2010; Gold et al., 2013; Yow and Li, 2015). Yet there are studies indicating that there was no such advantage and methodological differences with respect to the task or the type of bilinguals between different studies could have contributed to the contradictory findings (Hilchey and Klein, 2011; Paap and Greenberg, 2013; Paap and Sawi, 2014; Valian, 2015; Nichols et al., 2020; Ware et al., 2020). Additionally, since bilingual language experience is complex with multiple aspects including age of acquisition, language proficiency, language usage, etc., to what extent language experience impacts cognitive performance is still not clear. Therefore, in this study, we aim at discussing some issues that have been raised in this debate about whether a bilingual EF advantage exists and the extent and specificity of the effects of bilingualism on cognition, especially in older adults.

One of the fundamental issues with prior studies on bilingualism and EF lies in the varied ways of defining and measuring bilingualism. How one is defined as a bilingual in the literature has been inconsistent, and the diversity of language and social background underlying the monolingual and the bilingual groups makes it challenging to consolidate the literature (see Surrain and Luk, 2019 for a detailed review). Consequently, how to measure bilingualism has become a critical issue of recent interest (Bialystok, 2021; Kremin and Byers-Heinlein, 2021). Kremin and Byers-Heinlein (2021) discussed how different studies have applied various arbitrary cut-offs to define groups of monolinguals and bilinguals, making it difficult to synthesize the results across studies. Traditionally, the focus of bilingualism research has been on categorizing individuals based on their language experience, i.e., either a speaker is a monolingual or a bilingual. To classify one as monolingual or bilingual, researchers typically consider variables such as language proficiency, second language age of acquisition (L2 AoA), or language usage. For example, in Bialystok et al. (2004) Study 1, participants were grouped as monolingual or bilingual based on their language profile (i.e., AoA, daily usage, and proficiency). In their study, the bilingual participants were educated in English and Tamil from age 6, had used both languages daily (i.e., average daily usage was 56% for English and 44% for Tamil) throughout their lives, and were equally proficient in both languages, whereas the monolingual speakers used only English in their daily life and were not functionally fluent in any other language despite taking language courses in school. Similarly, Houtzager et al. (2017) applied the dichotomy to categorize their participants as either monolingual speakers (German speakers) or bilingual speakers (Dutch and Frisian speakers who had acquired both languages before the age of 6 and have been using both languages ever since). Paap and Greenberg (2013), on the other hand, used language proficiency as a sole measure of bilingualism. They asked students to rate their speaking and listening proficiency on a 7-point scale (1 = *beginner* to 7 = *super fluency*) for the languages they knew. Participants were classified as bilinguals if they rated language proficiency as a 4 (= *advanced intermediate*) or higher in more than one language, and otherwise monolinguals if they rated English proficiency as a 4 or higher and rated all other languages as below 4. In a more recent large-scale study of 11,041 participants, Nichols et al. (2020) grouped participants as monolingual or bilingual based on only one question (i.e., "how many languages do you speak"), such that bilinguals were defined as those who self-reported speaking two or more languages and monolinguals as those who self-reported speaking only one language. Even among studies that have focused on the same variable of bilingual experience (e.g., AoA, usage, or proficiency) in defining bilingualism, the exact definition or cut-offs can be different from study to study. For example, Hoff et al. (2012) defined bilingual children as those who had at least 10% exposure to a second language regardless of home environment or others. In another study by Bedore et al. (2012), Spanish- English bilingual children were classified as "functional monolingual" if their dominant language use was between 80% and 100% (or 0%–20% in the other language), meanwhile, children were classified as "Bilingual Dominant" if the use of their dominant language was between 60% and 80%, or as "Balanced Bilingual" if between 40% and 60%. In sum, these studies showed that categorizing language experience could be challenging, and different studies varied greatly in their criteria for defining who is a bilingual and who is not.

In recent research, scholars have raised the issue of the complexity and heterogeneity of bilingual language experiences, such as individual differences in language exposure and group diversity, and thus have suggested to treat bilingualism as a continuous variable instead of a dichotomous variable (Luk and Bialystok, 2013; Yow and Li, 2015; Hartanto and Yang, 2019; Grundy, 2020). Applying continuous measurements would provide a more fine-grained and precise way of measuring individual differences compared to categorical measures. For example, Incera and McLennan (2018) reiterated the importance of considering dual-language usage and age as continuous variables when studying the effects of bilingualism in younger and older adults. In addition, Chan et al. (2020) considered balanced bilingual usage and language-switching frequency as two continuous predictors of four different EF tasks (Stroop task, the spatial 2-back task, the color-shape switching task, and the flanker task) in bilingual older adults. Recently, Kremin and Byers-Heinlein (2021) suggested that to suit the variations of individual study, researchers could aim to apply both a categorical approach and a continuous approach to better capture the underlying construct of each study. In sum, different approaches to defining and measuring bilingualism were used in different studies, and this no doubt contributes to a large extent to the conflicting results in bilingualism and EF reported in the field so far. Hence, it is vital that researchers thoroughly evaluate these different measurements when studying bilingualism, especially in view of the complexity and context of the local populations (van den Noort et al., 2019; Bialystok, 2021; Kremin and Byers-Heinlein, 2021).

So far, we have discussed some fundamental issues in bilingual research. In addition to these issues, there has been significant interest in studying the effect of bilingualism on cognition in later life, given the rapid aging society. It is well known that executive function abilities are impaired in normal and pathological aging (e.g., Gates et al., 2010; McGuinness et al., 2010). Bilingualism has been identified as an important lifestyle factor that can increase cognitive reserve, i.e., the brain's capacity to maintain intact cognitive function in the advent of brain injury, disease, or aging, as a result of neuroplasticity and functional reorganization (e.g., Antoniou and Wright, 2017; Bialystok et al., 2021). It is suggested that the constant practice of language control (i.e., regularly managing two or more languages) in bilingual individuals strengthens and maintains the neural networks involved in these processes, and such positive neural adaptations may not only lead to enhance cognitive performance in healthy older adults but also benefit older adults with cognitive impairment or dementia (e.g., Grady et al., 2015; Chan et al., 2020; see Bialystok et al., 2021, for a review). There are several studies showing how being bilingual (vs. monolingual) could attenuate cognitive declines associated with neurodegenerative diseases (e.g., Craik et al., 2010; Alladi et al., 2013; see Anderson et al., 2020, for a meta-analysis). For instance, lifelong bilingualism (defined as speaking two or more languages at least from early adulthood) was reported to delay the onset of symptoms of dementia for 4 to 5 years (Bialystok et al., 2007; Freedman et al., 2014). However, inconsistencies exist between studies that support the benefits of bilingualism in cognitive aging and those that fail to find such evidence, which could be attributed to individual variations in bilingual experience in the literature (Zhang et al., 2020). Therefore, more systematic investigations of older participants' bilingual experience in relation to their cognitive performance are necessary. This requires going beyond treating bilingualism as a dichotomous variable, i.e., either monolingual or bilingual (see also Bialystok et al., 2014; Voits et al., 2022). Although a few recent studies have attempted to examine individual variation in bilingual experience (e.g., degree of bilingual usage or proficiency) and executive function in aging and neurodegenerative diseases (Borsa et al., 2018; Calabria et al., 2020), our knowledge about the extent and specificity of the effects of bilingualism is still limited. In this study, we aim to explore the two most common approaches to defining and measuring bilingualism (i.e., categorical and continuous approaches) and their associations with executive functioning in older adults with and without cognitive impairment in the context of the local bilingual population in Singapore.

The current study

In this study, we examine how different methods of measuring bilingualism might yield varying results on the performance of a single EF task among cognitively healthy and cognitively impaired older adults. We investigate (1) the categorial approach, grouping participants into two categories based on their dominant language use as per Bedore et al. (2012), namely, Bilingual Dominant (more usage in the dominant language and less in other languages) and Balanced Bilingual, with different cut-offs for categorization, and (2) the continuous approach, measuring bilingualism along a continuum of more and less dominant language use. The study would, on the one hand, highlight the limitations and criticisms of arbitrary cut-off of dominant language usage to measuring bilingualism, which was commonly exploited in the past studies and on the other hand, offer an opportunity to investigate the relation between EF and bilingualism in older adults.

We applied a task-switching paradigm, i.e., the color-shape switching task, in this study. The task allows us to study the complexity of EF, namely, mixing cost, switching cost, and global reaction time. Mixing cost is related to long-term overall maintenance of the activation of two different tasks, whereas switching cost is related to local time-sensitive processing and management of two tasks and reflects the efficiency in initiating the current task while inhibiting the interference of the previous task (Kray and Lindenberger, 2000; Rubin and Meiran, 2005; Prior and MacWhinney, 2010). In addition, global reaction time is used to assess the ability to constantly monitor and evaluate the need for cognitive control to resolve conflict (i.e., conflict monitoring; see Lehtonen et al., 2018; Chan et al., 2020). Despite several studies that have investigated bilingualism and EF performance using the task-switching paradigm with the normal aging population (e.g., Kray and Lindenberger, 2000; Gold et al., 2013; Chan et al., 2020), few have explored the relation between various dimensions of bilingualism and task-switching performance among older adults with cognitive impairment. Here, we use the color-shape switching task to examine the effects of bilingualism in various set-shifting costs both in normal aging and in pathological aging.

Before we introduce the study design, it is necessary for us to understand the language environment where our study participants came from. The participants live in Singapore, a multilingual and multicultural society with the largest ethnic group within the country being Chinese (about 74% of the total population). Within the Chinese community, there are several regional Chinese varieties or dialects that people use in the community, e.g., Mandarin, Hokkien, Hainanese, Hakka, Cantonese, Teochew, etc. Most older adults in Singapore are fluent bilingual speakers residing in a society where residents commonly engage in dual-language and dense code-switching (Ooi et al., 2018). However, there is also substantial variability in individual usage of the languages (from predominantly one language to a balanced use of two languages; see Yow and Li, 2015; Chan et al., 2020; Hartanto and Yang, 2020). Thus, for Singaporean older adults who are proficient in both languages, the extent of usage of these languages becomes a crucial variable in measuring their level of bilingualism. Furthermore, if the degree of bilingualism affects cognitive performance, specifically set-shifting costs in the present study, then Balanced Bilinguals, who use two languages more often than a single language would outperform Bilingual Dominants who predominantly use only one language. We expect that this hypothesis would apply to both cognitively healthy (CH) bilingual older adults and cognitively impaired (CI) bilingual older adults. Specifically, it is expected that Balanced Bilingual CH older adults will exhibit better cognitive performance compared to Bilingual Dominant CH older adults, and Balanced Bilingual CI older adults will outperform Bilingual Dominant CI older adults. Importantly, to address the issue of inconsistent results due to studies applying different cut-offs of language usage (Kremin and Byers-Heinlein, 2021), various cut-offs of the language usage were applied in the analyses of this study, which is also in line with the diverse linguistic profiles of the Singaporean older adults.

Methods

Participants

Fifty-two CH older adults and 46 CI older adults were recruited from four different elderly day care centers in Singapore as part of a larger cognitive intervention study. The inclusion criteria for the study were: (1) 40 years old and above, and (2) speak at least two of the following four languages: English, Mandarin, Hokkien, and Cantonese. One CI older adult was initially recruited but was excluded from the study because the participant did not meet the inclusion criteria. Four CH older adults and three CI older adults were excluded from the analysis because of incomplete data. Thus, there were a total of 48 CH older participants ($M_{\text{age}} = 73.25$ years, range = 53–90; 31 females) and 43 CI older participants ($M_{\text{age}} = 79.72$ years, range = 62–96; 33 females) in the final study sample. The dementia status of the CI older participants, as reported by the elderly day care centers, ranged from mild to moderate with three types of dementia, i.e., Alzheimer's disease, vascular dementia, and mixed dementia. Demographic information, including age, gender, monthly household income, years of education, and the Mini-Mental State Exam (MMSE) score, was collected (see Table 1). This study had been approved by the university IRB board (IRB-18-176).

Language background information and bilingualism measures

A language background questionnaire was used to collect the participants' language background details, including L2 AoA, language proficiency, and language usage, and the questionnaire was developed based on the one from Chan et al. (2020). While CH older participants completed the questionnaire by themselves, CI older participants had their caregivers complete the questionnaire for them (due to their cognitive status). All participants reported knowing two or more languages: 11 participants (3 CH older adults, 8 CI older adults) knew only two languages, 33 of them (14 CH older adults, 19 CI older adults) knew three languages, and the remaining 47 (31 CH older adults, 16 CI older adults) knew four languages. However, on average, participants reported minimal usage of their third- ($M = 6.69\%$ and 5.81% for CH and CI group, respectively) and fourth-most used languages ($M = 1.90\%$ and 0.92% for CH and CI group, respectively), hence they were considered as bilinguals for the purpose of this study.

For L2 AoA, participants reported an approximate age range (e.g., 0–6 or 7–18 years) when they first learned their second language. A total of 50 participants (26 CH older adults, 24 CI older adults) had learned a second language before age 6, and the rest of the 41 participants (22 CH older adults, 19 CI older adults) had learned a second language between ages 7 and 18. Language proficiency in reading, writing, listening, and speaking were reported on a scale from 0 (*beginner*) to 5 (*native*) and then summed up to obtain a composite score. If there were no unitary standardized written scripts for the languages reported, such as Hokkien, Cantonese, Teochew, only listening and speaking scores were recorded and computed. All participants across CH and CI groups were considered as proficient bilingual speakers (most and second most-proficient language score for CH: $M_{CH1} = 4.64$, $SD_{CH1} = 0.63$, $M_{CH2} = 3.95$, $SD_{CH2} = 0.94$ and CI: $M_{CI1} = 4.17$, $SD_{CI1} = 0.83$, $M_{CI2} = 3.80$, $SD_{CI2} = 1.10$).

Regarding language usage, participants first estimated the percentage of time spent in four different social contexts (i.e., with family, colleagues, friends, and others) in a typical week. Then, they reported the current usage frequency (in percentage) of each language in each of these contexts. A usage score was calculated for each language to indicate its frequency of use across the various social contexts. The average percentage of usage of the most used language (i.e., "dominant language usage") was 64.30% ($SD = 21.04\%$) and 69.09% ($SD = 16.40\%$) for CH and CI older participants respectively, while the average usage of the second-most used language was 23.36% ($SD = 15.79\%$) and 22.67% ($SD = 12.04\%$) for CH and CI older participants respectively.

Participants' language usage data was used to derive six bilingualism measurements based on dominant language usage: five categorical measurements and one continuous measurement. For each categorical measurement, participants were either categorized as Bilingual Dominant or Balanced Bilingual by using the following cut-offs, such as 90%, 80%, 70%, or 60% dominant language usage, or the median split of dominant language usage ($CH_{\text{median-split}}$: 61.29% dominant language usage; $CI_{\text{median-split}}$: 70% dominant language usage). For example, in cases where categorical measurement with a 90% cut-off was used, a participant was classified as Bilingual Dominant if they predominantly used one language for more than 90% of the time and the other language for $<10\%$ of the time (per week). Additionally, the measure of dominant language usage itself was applied as a continuous variable, indicating the degree of bilingual language usage.

Executive function task and measures

The study was conducted between July 2019 and June 2021. It is important to note that the first COVID-19 case in Singapore was detected on January 23, 2020, after we started our data collection. From April 3, 2020, to June 1, 2020, Singapore imposed a lockdown period for 3 months, where no one was allowed to leave their house unless for essential services. Subsequent Phases 1, 2 and 3 of various levels of restrictive measures continued to be implemented in elder-care centers through 21 November 2021 (www.moh.gov.sg). As a result, the color-shape switching task, programmed on MATLAB (2016b version) using the Psychophysics Toolbox (Version 3.0.15), was first administered on a MacBook Pro 13″ Laptop by a researcher in person before the COVID-19 lockdown period, and thereafter was converted to an online version using the Gorilla platform (Anwyl-Irvine et al., 2020) and administered remotely. There were 23 CI older adults and 36 CH older adults who completed the task using the MacBook. The remaining 20 CI older adults and 12 CH older adults completed the task on the Gorilla platform. Preliminary analyses revealed that there were no significant differences in mean reaction time between these two platforms ($ps > .73$), and hence all the participants' data from the two different platforms were collapsed in the final analyses.

The color-shape switching task was adapted from Prior and MacWhinney (2010). In this task, participants were instructed to

TABLE 1 Demographics and language characteristics of participants in the study.

	Cognitively healthy group		Cognitively impaired group		*p*
	n/M	*SD*	*n/M*	*SD*	
N	48		43		
Gender: female/male	31/17		33/10		.21
Age in years	73.25	8.68	79.72	7.62	<.001
MMSE score[a]	26.15	4.30	17.09	4.94	<.001
Education in years	9.42	5.45	5.26	5.00	<.001
Household monthly income with 1–4 scale[b]	1.56	0.97	1.51	0.84	.44
L2 AoA: 0–6 years/7–18 years	25/23		24/19		.72
Language proficiency[c] $_{\text{most proficient language}}$	4.40	0.81	4.35	0.87	.79
Language proficiency[c] $_{\text{2nd−most proficient language}}$	4.25	0.79	3.99	0.83	.12
Dominant language usage score in %	63.30	21.04	69.09	16.40	.18

MMSE, Mini-Mental State Exam; L2 AoA, Second language age of acquisition. The *p*-values reported here are results of Pearson's chi-square test for gender and L2 AoA, Wilcoxon sum of ranks test for age, MMSE, education, language proficiency, dominant language usage score and Fisher's exact test for monthly household income. [a]The overall score is 30. We used the education-adjusted cut-off scores recommended for multiethnic Asian populations (Chua et al., 2019): a score of 19 or below is classified as cognitively impaired for individuals whose highest education level is primary school, and 23 or below for secondary school graduates. [b]Participants reported their monthly household income on the scale of 1–4: 1 = *less than SGD$2,000*, 2 = *SGD$2,000 to less than SGD$3000*, 3 = *SGD$3,000 to less than SGD$5,000*, or 4 = *above SGD$5,000.* [c]Participants self-reported their language proficiency on the scale of 0–5: 0 = *beginner* to 5 = *native-like proficiency*.

categorize a target stimulus either by its color (red or green) or by its shape (triangle or square) according to the task cue (see Figure 1). The color task cue was a color gradient strip, and the shape task cue was an array of white dots. In each trial, participants first saw a centered fixation cross lasting for 350 ms, followed by a blank screen for 150 ms. The task cue then appeared on the screen (above the screen center) for 250 ms. This was followed by the centered target stimulus, which remained on screen until a response is made or 5,000 ms has lapsed. The next trial started automatically afterwards. Responses were by key press: "O" for red or triangle and "P" for green or square.

Participants completed a practice block (12 practice trials) followed by two single-cue blocks and four mixed-cue blocks (24 test trials per block). The practice trials were identical to the test trials and served to familiarize the participants with the task; thus, they were not included in the analysis. Two additional warm-up trials were added at the beginning of each test block and were excluded from analysis. Each single-cue block contained only one type of task cue (i.e., *single-task trials*), and participants completed a block of color-task trials and a block of shape-task trials (order counterbalanced across participants). Each mixed-cue block contained an equal number of color- and shape-task trials that appeared in a pseudo-random order. Importantly, half of the trials in the mixed-cue block were *non-switch trials*, where the current task was the same as the previous trial (e.g., color-color), and the other half were *switch trials*, where the current task was different from the previous trial (e.g., color-shape).

Three measures of EF were derived from participants' reaction times (RTs) in the test trials: mixing cost, switching cost, and global RT. Following previous work using task-switching paradigms (e.g., Prior and MacWhinney, 2010; Chan et al., 2020), mixing cost was calculated as the increase in mean RT on the non-switch trials in the mixed-cue blocks vs. the single-task trials in the single-cue blocks, and switching cost was the difference in mean RT between the switch trials and the non-switch trials in the mixed-cue blocks. Global RT was defined as the mean RT for trials in the mixed-cue blocks. For RT calculation, only trials with correct response were included (CH group: $M_{\text{accuracy}} = 90.31\%$, CI group: $M_{\text{accuracy}} = 72.93\%$), excluding any trials with RT below 200 ms or above 2.5 *SD* of the group mean.

Procedure

This study was part of a cognitive intervention program. Before starting the intervention program, all participants participated in two sessions of a series of cognitive testing, which included the color-shape switching task and the Raven's progressive matrices, as well as a set of questions on language background and attitudes toward technology. Each session lasted around 2 hours and the testing order of the tasks was pseudo randomized. Informed consent was obtained from all participants prior to the start of their testing.

Data analysis plan

We ran separate analyses for the CH older adult participants and the CI older adult participants because the two groups of participants varied significantly in terms of their age, MMSE score,

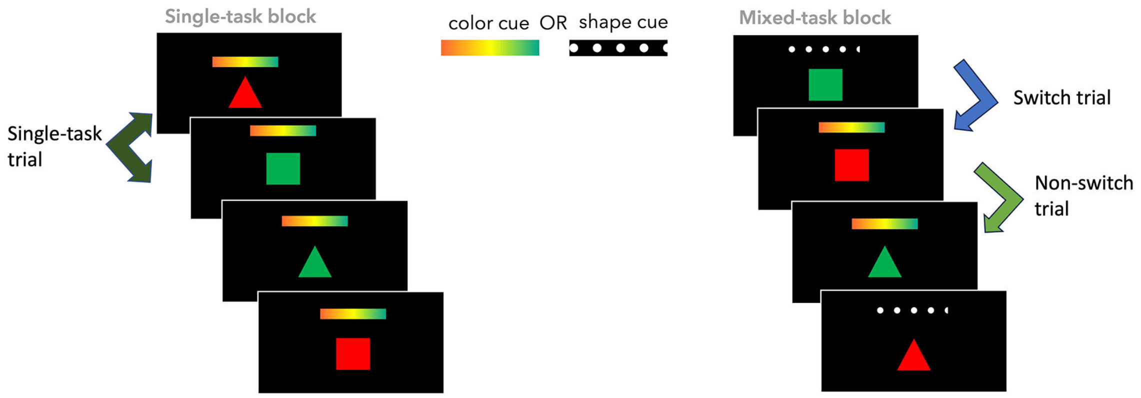

FIGURE 1
Design of the color-shape switching task (Prior and MacWhinney, 2010). Three measures of executive function were derived from participants' reaction time (RT) in different test trials. Switching cost was the difference in mean RT between the switch trials and non-switch trials in the mixed-cue blocks. Mixing cost was the difference in mean RT between the non-switch trials in the mixed-cue blocks and the single-task trials in the single-cue blocks. Global RT was the mean RT in the mixed-cue blocks.

and years of education (as seen in Table 1) and it was not our aim to compare performance between the two groups. We applied linear mixed-effect models (Baayen et al., 2008) using the lme4 R package (Bates et al., 2014) in the R-Studio environment (Version 4.2.1) for analyses. To examine the effect of different cut-offs of dominant language usage on task switching performance, for each EF measure (i.e., mixing cost, switching cost, and global RT), we constructed a model that included a fixed effect of the bilingualism variable (either categorical or continuous) as the main predictor of EF performance. We also included age, education and income as fixed effects, and different platforms as random intercepts.[1] We interpreted the results assuming that only one categorization had been conducted, and not as multiple comparisons between cut-offs; hence, we did not adjust the p-values for multiple comparisons and only reported the unadjusted p-values in the Results section.[2]

Results

A summary of the participants' demographic information in our analyses of bilingualism is displayed in Table 2. For visualization (i.e., boxplots and scatterplots) of the data described in this section, see Figures 2–4. Additionally, a table featuring the mean response times for the EF measurements across all groups is available in the Supplementary material. Overall, the study did not find a bilingual effect on executive function using 90%, 80%, 60% dominant language (L1) usage cut-off, and the median split of dominant language (L1) usage as well as dominant language usage as a continuous variable for CH older adults. However, the study did find a bilingual effect on executive function using 70% dominant language (L1) usage cut-off.

Categorical approach: 90% cut-off

There were 8 CH older adults classified as Bilingual Dominant speakers and 40 CH older adults classified as Balanced Bilingual speakers. They were not significantly different in age, education, and monthly income, all $ps > .06$.[3] Five CI older adults were classified as Bilingual Dominant speakers, and 38 CI older adults were classified as Balanced Bilingual speakers. Both groups did not significantly differ in age, education, and monthly income either, all $ps > .10$. For both CH older adults and CI older adults, there were no significant differences between the Bilingual Dominant and Balanced Bilingual speakers in the three EF measurements, i.e., mixing cost, switching cost, and global RT (CH: $ps > .15$; CI: $ps > .49$).

Categorical approach: 80% cut-off

Thirteen CH older adults were classified as Bilingual Dominant speakers and 35 CH older adults classified as Balanced Bilingual speakers, with no significant between-group differences in age, education, and monthly income, all $ps > .10$. Thirty CI older adults were classified as Balanced Bilingual speakers and 13 CI older adults were classified as Bilingual Dominant speakers, and the two groups were not significantly

1 Raven's progressive matrices was used as the measurement for the non-verbal fluid intelligence (Raven and Court, 1998) and it was planned as one of the control variables in the model. However, it was not included in the end as the results were not correlated with any task switching costs both for CH older adults and CI older adults (Spearman correlations$_{CH-OA}$, $ps > .13$, Spearman correlation$_{CI-OA}$, $ps > .12$). The model is included here: EF measure ∼ bilingualism predictor + age + education + income + (1|platform).

2 Considering the number of tests (6) conducted with the same data, a Bonferroni corrected alpha value of .0083 (equal to .05/6) would be necessary to achieve statistical significance after adjusting for multiple comparisons.

3 We used nonparametric tests to compare all demographic information between the two groups: Wilcoxon sum of ranks for age, MMSE, education, language proficiency, and dominant language usage score, and Fisher's exact test for monthly household income. This applies to all group comparisons reported in this study.

TABLE 2 Summary of participant characteristics for different analysis in the study.

	Continuous approach	Categorical: 90% cut-off		Categorical: 80% cut-off	
	All *n/M (SD)*	Bilingual dominant *n/M (SD)*	Balanced bilingual *n/M (SD)*	Bilingual dominant *n/M (SD)*	Balanced bilingual *n/M (SD)*
Cognitively healthy group					
N	48	8	40	13	35
Gender: female/male	31/17	4/4	27/13	7/6	24/11
Age in years	73.25 (8.68)	77.00 (7.15)	72.50 (8.84)	75.00 (9.00)	72.60 (8.60)
Education in years	9.42 (5.45)	5.75 (5.20)	10.15 (5.25)	9.38 (7.33)	9.43 (4.69)
Household monthly income with 1–4 scale[a]	1.56 (0.97)	1.25 (0.71)	1.63 (1.00)	1.85 (1.14)	1.46 (0.89)
L2 AoA: 0–6 years/7–18 years	25/23	4/4	21/19	7/6	18/17
Language proficiency[b]$_{\text{most proficient language}}$	4.40 (0.81)	4.47 (0.78)	4.43 (0.79)	4.54 (0.65)	4.40 (0.83)
Language proficiency[b]$_{\text{2nd-most proficient language}}$	4.25 (0.79)	3.59 (1.34)	4.02 (0.85)	3.62 (1.21)	4.07 (0.81)
Dominant language usage in %	63.30 (21.04)	97.48 (3.20)	57.67 (16.15)	92.96 (6.65)	53.66 (12.88)
Cognitively impaired group					
N	43	5	38	13	30
Gender: female/male	33/10	4/1	29/9	9/4	24/6
Age in years	79.72 (7.62)	76.20 (6.91)	80.18 (7.68)	78.69 (7.26)	80.17 (7.85)
Education in years	5.26 (5.00)	3.60 (2.30)	5.47 (5.23)	4.54 (5.71)	5.57 (4.72)
Household monthly income with 1–4 scale[a]	1.51 (0.84)	2.20 (1.10)	1.52 (0.83)	1.92 (1.00)	1.45 (0.80)
L2 AoA: 0–6 years/7–18 years	24/19	4/1	20/18	8/5	16/14
Language proficiency[b]$_{\text{most proficient language}}$	4.35 (0.87)	4.55 (0.62)	4.31 (0.90)	4.40 (0.69)	4.32 (0.96)
Language proficiency[b]$_{\text{2nd-most proficient language}}$	3.99 (0.83)	3.20 (1.19)	3.88 (1.09)	3.02 (0.86)	4.14 (1.04)
Dominant language usage score in %	69.09 (16.40)	93.40 (2.99)	65.90 (14.63)	88.21 (5.03)	60.82 (12.03)

	Categorical: 70% cut-off		Categorical: 60% cut-off		Categorical: median split	
	Bilingual dominant *n/M (SD)*	Balanced bilingual *n/M (SD)*	Bilingual dominant *n/M (SD)*	Balanced bilingual *n/M (SD)*	Bilingual dominant *n/M (SD)*	Balanced bilingual *n/M (SD)*
Cognitively healthy group						
N	16	32	25	23	24	24
Gender: female/male	9/7	22/10	18/7	13/10	17/7	14/10
Age in years	75.44 (8.32)	72.16 (8.78)	75.20 (7.89)	71.13 (9.17)	74.17 (8.03)	72.33 (9.37)
Education in years	8.88 (6.82)	9.69 (4.71)	8.64 (6.27)	10.26 (4.36)	9.33 (6.24)	9.50 (4.65)
Household monthly income with 1–4 scale[a]	1.75 (1.06)	1.47 (0.92)	1.68 (1.07)	1.43 (0.84)	1.79 (1.10)	1.33 (0.76)
L2 AoA: 0–6 years/7–18 years	9/7	16/16	12/13	13/10	12/12	13/11
Language proficiency[b]$_{\text{most proficient language}}$	4.66 (0.69)	4.62 (0.60)	4.36 (0.86)	4.52 (0.70)	4.73 (0.60)	4.54 (0.65)
Language proficiency[b]$_{\text{2nd-most proficient language}}$	3.81 (1.18)	4.02 (0.81)	4.37 (0.75)	4.52 (0.66)	3.95 (1.06)	3.95 (0.82)

(Continued)

TABLE 2 (Continued)

	Categorical: 70% cut-off		Categorical: 60% cut-off		Categorical: median split	
	Bilingual dominant *n/M (SD)*	Balanced bilingual *n/M (SD)*	Bilingual dominant *n/M (SD)*	Balanced bilingual *n/M (SD)*	Bilingual dominant *n/M (SD)*	Balanced bilingual *n/M (SD)*
Dominant language usage in %	90.02 (8.78)	51.44 (11.04)	80.98 (14.23)	46.17 (8.09)	80.70 (15.88)	47.90 (9.57)
Cognitively impaired group						
N	20	23	29	14	20	23
Gender: female/male	14/6	19/4	22/7	11/3	14/6	19/4
Age in years	79.55 (7.91)	79.87 (7.54)	80.76 (7.64)	77.57 (7.40)	80.15 (7.60)	79.35 (7.80)
Education in years	4.15 (4.96)	6.22 (4.94)	4.38 (5.07)	7.07 (4.48)	4.15 (4.96)	6.22 (4.94)
Household monthly income with 1–4 scale [a]	1.58 (0.90)	1.45 (0.80)	1.56 (0.89)	1.43 (0.76)	1.58 (0.90)	1.45 (0.80)
L2 AoA: 0–6 years/7–18 years	12/8	12/11	16/13	8/6	13/7	11/12
Language proficiency$^{b}_{\text{most proficient language}}$	4.14 (0.86)	4.21 (0.80)	4.29 (0.98)	4.44 (0.65)	4.09 (0.84)	4.25 (0.82)
Language proficiency$^{b}_{\text{2nd-most proficient language}}$	3.49 (1.20)	4.08 (0.96)	3.74 (0.82)	4.34 (0.73)	3.61 (1.11)	3.97 (1.11)
Dominant language usage in %	83.68 (7.70)	56.42 (10.05)	78.30 (10.46)	50.04 (7.33)	83.61 (7.83)	56.48 (10.14)

Standard deviations are presented in parentheses. L2 AoA, Second language age of acquisition. [a]Participants reported their monthly household income on the scale of 1–4: 1 = *less than SGD$2,000*, 2 = *SGD$2,000 to less than SGD$3,000*, 3 = *SGD$3,000 to less than SGD$5,000*, or 4 = *above SGD$5,000.* [b]Participants self-reported their language proficiency on the scale of 0–5: 0 = *beginner* to 5 = *native-like proficiency*.

different in their age, education, and monthly income, all *ps* > .23.

Regarding EF performance, we did not find any difference in task performance between the Bilingual Dominant and Balanced Bilingual speakers for both CH older adult group and CI older adult group (CH: *ps* > .25; CI: *ps* > .40).

Categorical approach: 70% cut-off

For CH older adults, Bilingual Dominant speakers ($n = 16$) and Balanced Bilingual speakers ($n = 32$) did not differ significantly in age, education, and monthly income, all *ps* > .25. For CI older adults, similarly, Bilingual Dominant speakers ($n = 20$) and Balanced Bilingual speakers ($n = 23$) were not significantly different in age, education, and monthly income, all *ps* > .09.

Results of the mixed-effect model showed a significant effect of grouping (Bilingual Dominant vs. Balanced Bilingual) on both mixing cost, $b = 260.63$, $SE = 123.72$, $z = 2.11$, $p = .04$, and global RT, $b = 257.96$, $SE = 121.12$, $z = 2.13$, $p = .04$, for the CH older adults. Specifically, compared to Bilingual Dominant CH speakers, Balanced Bilingual CH speakers demonstrated a smaller mixing cost as well as a faster overall RT. However, there was no significant difference between the two groups of CH older adults in their switching cost, $b = -48.91$, $SE = 59.11$, $z = -0.83$, $p = .41$. For CI participants, there was no significant effect of group (Bilingual Dominant vs. Balanced Bilingual) on participants' task performance, including switching cost, mixing cost, and global RT, all *ps* > .68.

Categorical approach: 60% cut-off

For CH older adults, Bilingual Dominant speakers ($n = 25$) and Balanced Bilingual speakers ($n = 23$) were comparable in their age, education, and monthly income, all *ps* > .12. For CI older adults, Bilingual Dominant speakers ($n = 29$) and Balanced Bilingual speakers ($n = 14$) were significantly different in their education in years, $p = .03$, but not for age and monthly income, both *ps* > .26.

Regarding EF performance, we did not find any significant effect of grouping (Bilingual Dominant vs. Balanced Bilingual) on switching cost, mixing cost, or global RT, and this was true for both CH and CI participants (CH: *ps* > .49, CI: *ps* > .07).

Categorical approach: median split

For CH older adults, Bilingual Dominant speakers ($n = 24$) and Balanced Bilingual speakers ($n = 24$) were not significantly different in age, education, and monthly income (*ps* > .24). Besides, results revealed no significant effect of grouping for all EF measurements (*ps* > .42). For CI older adults, the grouping by median split resulted in the same outcomes as the grouping based on the 70% dominant language cut-off. Therefore, the results for CI older adults using the median split were identical to those described in Categorical approach: 70% cut-off: there was no significant effect of grouping on EF performance among CI older adults (*ps* > .68).

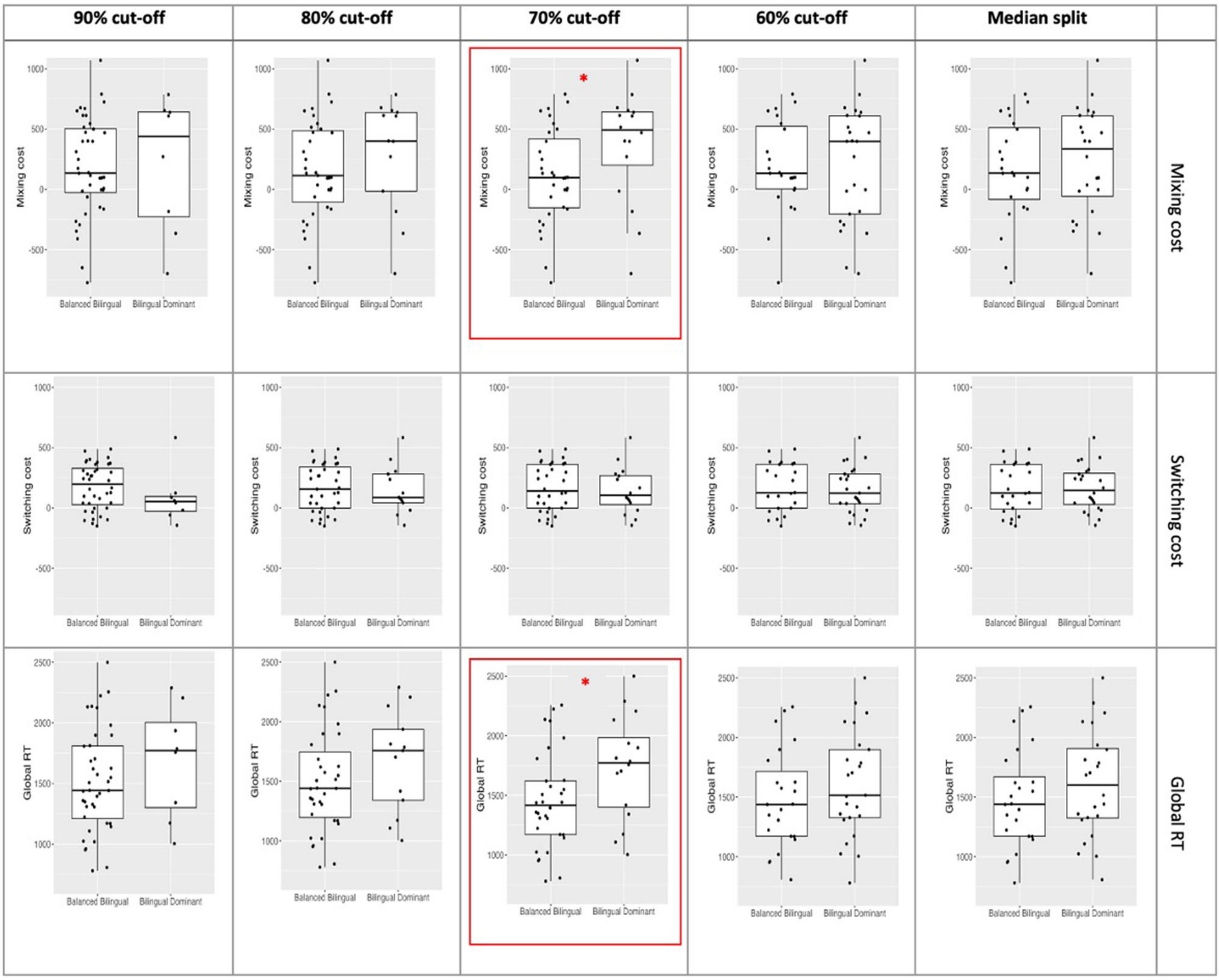

FIGURE 2
Results from categorical approaches: Comparison of EF performance between Bilingual Dominant and Balanced Bilingual groups (cognitively healthy group). *$p < 0.05$.

Continuous approach: dominant language usage score as a predictor

We considered dominant language usage as a continuous variable in the analysis. For CH older adults, the effect of dominant language use was not significant on EF measures (all $ps > .10$). On the other hand, for CI older adults, dominant language usage did not significantly influence their performance in the switching task (all $ps > .19$).

Discussion

It is important to reiterate that the purpose of the study was not to emphasize which method (categorical vs. continuous) or which cut-offs of defining bilingualism was better than the other. Rather, the aim of the study is to objectively examine how computations of dominant language usage in defining and measuring bilingualism could lead to different interpretations of the effect of bilingualism on EF in cognitively healthy older adults as well as older adults with cognitive impairment. Overall, different measurements of bilingualism yielded different results and the current study offers an opportunity to thoroughly scrutinize the relation between EF and a single language component, i.e., the dominant language usage with the two different populations, the cognitively healthy older adults and the cognitively impaired older adults. For example, when bilingualism was treated as a categorical variable based on dominant language usage (70% cut-off), we found that Balanced Bilingual CH speakers showed better goal maintenance performance and conflict monitoring ability (i.e., smaller mixing cost and faster global RT) than those dominant language CH speakers. For the CI older adults, however, there was no significant difference between the Bilingual Dominant and the Balanced Bilinguals in their task switching performance overall.

Our results appear to suggest that there is a positive bilingual effect on cognitively healthy older adults' executive function when participants were categorically classified as Bilingual Dominant or Balanced Bilingual with a 70% cut-off of dominant language usage.

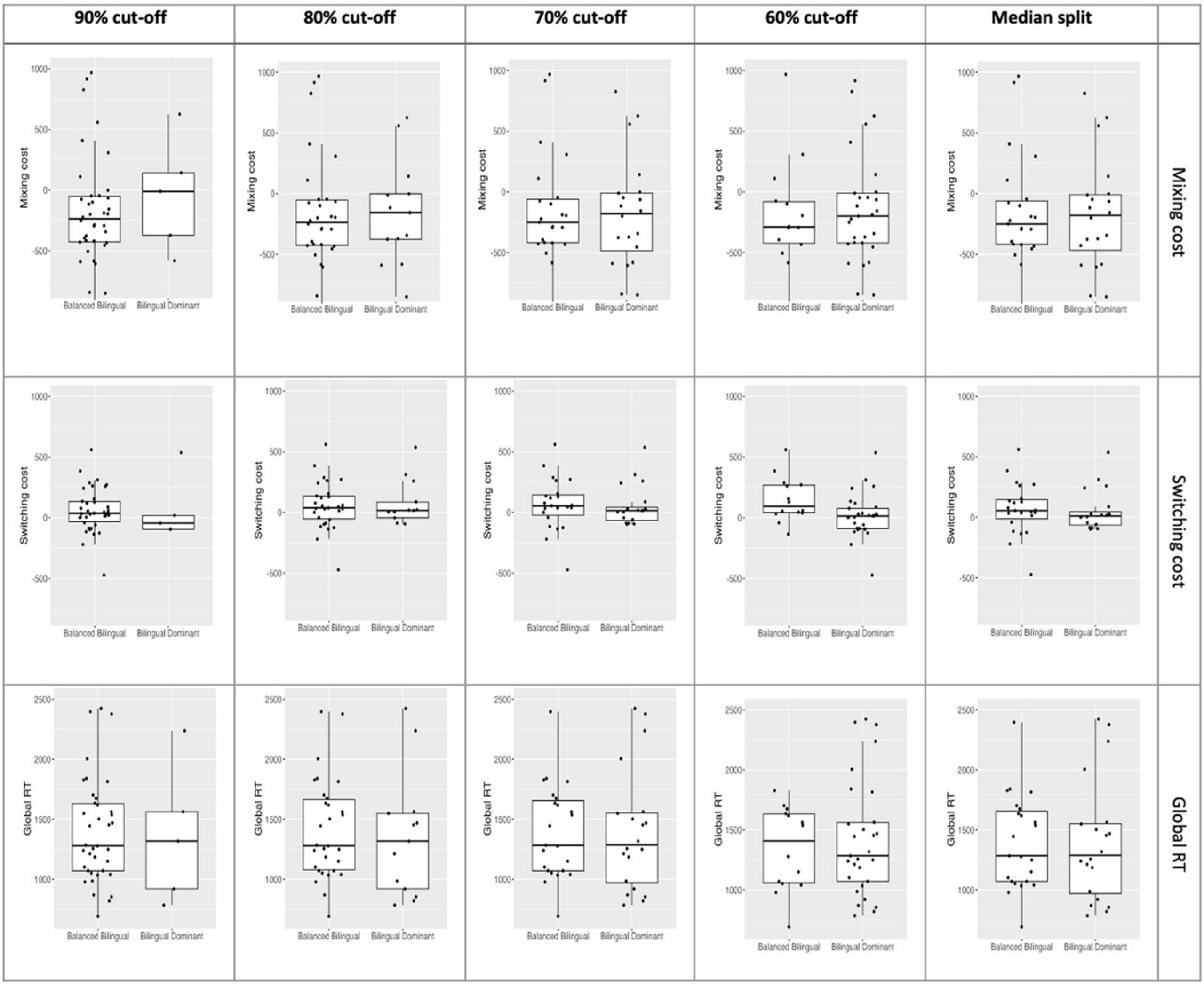

FIGURE 3
Results from categorical approaches: Comparison of EF performance between Bilingual Dominant and Balanced Bilingual groups (cognitively impaired group).

The cognitively healthy older participants who were Balanced Bilingual speakers (i.e., used more than one language regularly) outperformed their Bilingual Dominant peers (i.e., used only one language predominantly) on the task-switching task. They exhibited smaller mixing costs and faster global RT. However, this seemingly contrasts with Houtzager et al. (2017) findings, where they found smaller switching cost instead of smaller mixing cost in their bilingual older participants compared to the monolingual counterparts, even though both our study and Houtzager et al. applied the categorical approach of bilingualism. It is important to note that the way participants were classified as "monolingual" and "bilingual" in the two studies are different. In our study, participants were classified as Bilingual Dominant or Balanced Bilingual speakers based on whether they used one of their languages predominantly (70% of time as the cut-off for dominant language). So, the participants in our Bilingual Dominant group could, in fact, be considered as "functional" bilinguals—they acquired a second language before 18 years old and reported to be proficient in both languages. However, in Houtzager et al. (2017) study, they used "no proficiency in foreign languages" (p. 70) as the selection criterion for the monolingual group participants, who were compared with a group of bilinguals who became bilingual before age 6 and used both languages daily. Although Houtzager et al. (2017) study examined both bilingual and monolingual speakers, our study focuses on comparing bilinguals who predominantly use their dominant language to those who predominantly use their non-dominant language (Bilingual Dominant vs. Balanced Bilingual). Therefore, a possible explanation for these discrepant findings is that while the acquisition and proficiency of a second language may have enhanced the ability to switch between different mental sets (i.e., smaller switching cost, as in Houtzager et al., 2017), the regular use of two languages may have resulted in enhanced executive control for goal maintenance and conflict monitoring (i.e., smaller mixing cost and faster global RT in the current study). Nevertheless, this discrepancy reveals the weakness of using a categorical approach

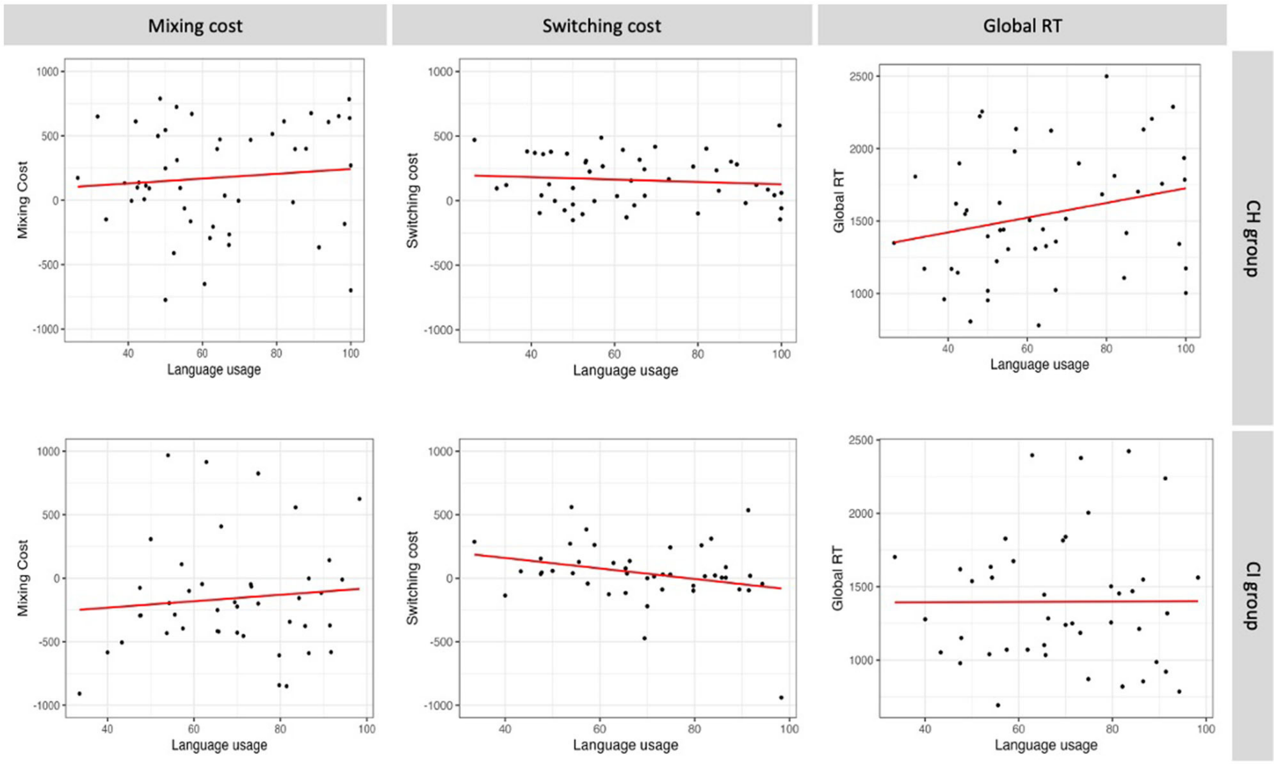

FIGURE 4
Scatterplots of switching task performance against dominant language usage (continuous). Among all participants, dominant language usage in % range = 26.35%–99.71%.

to defining and measuring bilingualism—different authors could "choose" how bilingualism is defined as well as different group comparisons, and such differences in the criteria for determining bilingualism could play a vital role in influencing the outcome of EF task performance. Besides, one needs to be cautious when interpreting the current results as the positive effect was only found in 70% cut-off, but not in the other groupings.

One would argue, then, that perhaps using a continuous approach toward determining bilingualism based on the same variable would resolve this problem. Several studies that applied the continuum approach appeared to reveal correlations between task switching and degree of bilingualism in usage. For example, Yow and Li (2015) found a smaller mixing cost associated with more balanced dual-language usage in university students, while Chan et al. (2020) found that faster non-switch trial RT and faster global RT were predicted by more balanced dual-language usage and less frequent language switching among cognitively healthy older adults. Our findings, however, did not find a significant relationship between "active bilingualism" and global RT when the dominant language usage was treated as a continuum. It is important to note that if only one categorization (such as using 70% cut-off) had been used, which is what most studies did, the results would have been statistically significant, as revealed by the unadjusted *p*-values in the current study. However, we caution against making unqualified claims about the significant effects of bilingualism on EF from the current study, as all of the significant effects reported here would not sustain the multiple-comparison correction. This study aims to critique how different computations of dominant language usage, when used to define bilingualism, could lead to different interpretations of its effects on EF performance.

Contrary to the effect of bilingualism found in CH older adults, we did not find any significant differences in performance between the Bilingual Dominant older adults with cognitive impairment and their Balanced Bilingual counterparts. In an early investigation by Schmitter-Edgecombe and Sanders (2009) using the letter-number switching task, they found that the cognitively healthy older adults and the cognitively impaired older adults were indifferent in the mixing cost (age range: 50–90, 52–89, respectively), but the cognitively healthy older participants had smaller switching costs than the cognitively impaired older adults. Hence, while mixing cost can be considered as an aging marker, switching cost deficit appears to be associated with abnormal aging process (Kray and Lindenberger, 2000; Wasylyshyn et al., 2011). Thus, one would expect the bilingual CI older adults to have smaller switching cost than their monolingual peers if bilingualism indeed confers protection of the older adults' cognitive reserve. But we did not find such evidence—the Balanced Bilingual CI older adults performed similarly as the Bilingual Dominant CI older adults. One major caveat of this study is that the language background information of the CI older participants was obtained from their caregivers and thus relies heavily on how much their caregivers know about the frequency and context of the participants' language usage. Another possible reason is that half of the CI older adults' data were collected during the COVID-19 lockdown period, which might have constrained the CI participants' general cognitive performance. Recent studies examining the impact of the COVID-19 pandemic reported that COVID-19-induced social isolation may impair cognitive functions across the adulthood lifespan (e.g., Castanheira et al., 2021; Fiorenzato et al., 2021; Noguchi et al., 2021). The pandemic has caused a substantial drop in older adults' in-person contact with non-resident family and friends (e.g., weekly contact from 61% before the outbreak to 39% during the outbreak; Freedman et al., 2021; a study of U.S. adults aged 70 and older), especially the cognitively and socially vulnerable older adults (e.g., Lehtisalo et al., 2021). The lack of social interaction in turn decreases opportunities for socially and cognitively stimulating activities in older adults, which may play an important role in maintaining language and cognitive functioning.

Finally, our work clearly has some limitations. First, in the current study, only one language variable, namely bilingual language usage, was thoroughly examined. However, other language variables, such as language switching, language proficiency, etc., could be included in future studies (Rodriguez-Fornells et al., 2012; Mann and de Bruin, 2022; Olson, 2022). In the introduction, we mentioned that different variables of bilingualism were applied in different studies, making it unclear to what extent bilingualism impacts cognitive performance. In this study, the relation between language usage and EF performance was examined in detail. Therefore, further research is needed to systematically investigate other bilingual variables. Apart from using a single language variable, another way of measuring bilingualism is to apply a composite score on several language variables based on the results of a factor analysis. Previous studies have used language information collected from the participants, performed a factor analysis to derive a composite score, and used them as a measure of bilingualism for further analysis (Luk and Bialystok, 2013; Dash et al., 2019, 2022; Calabria et al., 2020). Such a method considers the heterogeneous nature of bilingualism and allows researchers to combine various language variables, e.g., L2 AoA, L2 usage, and proficiency information, into one bilingualism score to avoid adjustment of p-value during multiple comparisons. However, individual factors, such as education levels, family income, age etc., should also be considered. Instead of treating these individual factors as random effects in an analysis model, another way of balancing out the differences between these factors is to calculate the propensity score (Rosenbaum and Rubin, 1983). This would allow us to match the confounded variables systematically with the target comparison groups. While our study has sought to focus on a single aspect of bilingualism (dominant language usage) and hence did not use a composite score in our analyses, future research should certainly consider using such approaches to study bilingualism.

Additionally, a more accurate way of obtaining language background data with participants with cognitive impairment is needed (rather than relying on caregivers' report). The context and circumstances in which the data were collected also played an important role. Parts of our data were collected during the COVID-19 lockdown period, which might have resulted in an inactive lifestyle and a decrease in social interaction and language diversity of the older adults. Therefore, it limits the conclusion our study has on the effects of dominant language use on executive functions of the older adults. Given that our findings are based on a relatively small sample size and unequal sample size for some groups (e.g., 90% cut-off: CH group: 8 vs. 40; CI group: 5 vs. 38; 80% cut-off: CH group: 13 vs. 35; CI group: 13 vs. 30; 70% cut-off: CH group: 16 vs. 32), and the issue of unequal variance within the groups, the statistical power of these analyses would be reduced. Therefore, the results from such analyses should be treated with caution (Snijders, 2005). Moreover, Costumero et al. (2020) discovered that although Spanish-Catalan speakers with mild cognitive impairments (MCI) did not differ from Spanish MCI speakers in their cognitive task performance (e.g., MMSE, Boston Naming, etc.) during the first testing, the monolingual speakers did worse in those tests during the second testing (6–9 months later after the first testing) compared to their bilingual peers. Therefore, a longitudinal study might help clarify the effects of bilingualism on executive functions in the abnormal aging process and buffer any temporary disruptions to social activities and social interactions in older adults (such as the COVID-19 pandemic). Last but not least, bilingualism as a factor for protecting against neurodegenerative diseases has been discussed in the last decade (Kavé et al., 2008; Craik et al., 2010; Schweizer et al., 2012), yet few studies have examined the various dimensions of bilingualism in individuals diagnosed of cognitive impairment (Voits et al., 2022). This study is one of the first to attempt to gain a more detailed understanding of how various categorizations of dominant language usage in bilingualism might seemingly influence the trajectory of cognitive decline in those already diagnosed with neurodegenerative disorders, despite methodological and sample limitations.

In sum, our findings have important implications for understanding the language data from both the normal aging population and the pathological aging population in more multifaceted ways than previous studies. We have specifically investigated the different computations of dominant language usage to measure bilingualism and examined the relation between the choice of bilingualism measurements and their effects on older adults' EF. It is important to note that our results do not imply that binary categories (e.g., dominant vs. non-dominant language usage) are more valid or more informative than continuous data just because we found significant results using this variable, or that bilingualism itself confers EF advantages. On the contrary, the divergent results (across six computations in a single sample) in the current study underscore the complexities of bilingualism and highlight the pitfalls of choosing one method over another (including arbitrary categorical split, such as 70% cut-off, or median split). The lack of consensus in the field may be, to a large extent, due to the different ways bilingualism is defined or measured in different studies. Finally, it is important to have a more fine-grain way of measuring bilingualism to help us better understand the relationship between EF and bilingualism in the future study.

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 Singapore University of Technology and Design IRB Board (IRB-18-176). The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent of the cognitively impaired participants for participation in this study was provided by the participants' legal guardians/next of kin, and cognitively healthy participants had provided their informed consent themselves.

Author contributions

H-CC and WQY contributed to the conceptualization and design of the study and reviewed and edited the paper. H-CC collected the data, conducted the analysis, and wrote the original draft. All authors contributed to the article and approved the submitted version.

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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.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/flang.2023.1165388/full#supplementary-material

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