Dual-task decrements in mono-, bi-, and multilingual participants: Evidence of multilingual advantage

Sameera M. Sidat[1], Anastasia Giannakopoulou[1], Christopher J. Hand[2], and Joanne Ingram[3*]

Published in *Laterality*: https://doi.org/10.1080/1357650X.2023.2178061

[1] School of Psychology, University of Bedfordshire, Luton, United Kingdom

[2] School of Education, University of Glasgow, United Kingdom

[3] Division of Psychology, University of the West of Scotland, Paisley, United Kingdom

*Corresponding Author
Dr Joanne Ingram
School of Education and Social Sciences,
University of the West of Scotland,
Paisley,
United Kingdom

Email: joanne.ingram@uws.ac.uk
Tel: +44(0)141 429 4429

Keywords: *asymmetry; bilingualism; dual-task performance; functional distance; lateralisation*

Abstract

Evidence suggests that language processing in bilinguals is less left-lateralised than in monolinguals. We explored dual-task decrement (DTD) for mono-, bi-, and multilinguals in a verbal-motor dual-task paradigm. We expected monolinguals to show greater DTD than bilingual participants, who would show greater DTD than multilingual participants. Fifty right-handed participants (18 monolingual, 16 bilingual, 16 multilingual) completed verbal fluency and manual motor tasks in isolation and concurrently. Tasks were completed twice in isolation (left-handed, right-handed) and twice as dual-tasks (left-handed, right-handed); participants' motor-executing hands served proxy for hemispheric activation. Results supported hypotheses. Completing dual-tasks incurred greater cost for manual motor tasks than for verbal fluency tasks. Negative cost of performing dual-tasks diminished as number of languages spoken increased; in fact, multilingual individuals demonstrated a dual-task advantage in both tasks when using the right hand, strongest in the verbal task. Dual-tasking had the greatest negative impact on verbal fluency of monolingual participants when the motor task was completed with the right hand; for bi- and multi-lingual participants, the greatest negative impact on verbal fluency was seen when the motor task was completed with the left hand. Results provide support for the bi-lateralisation of language function in bi- and multilingual individuals.

Introduction

The experience of speaking more than one language has been shown to provide bilingual and multilingual individuals with enhanced linguistic capabilities (Bialystok, 2001; Bialystok, 2017; Cenoz, 2013). These linguistic capabilities are subsequently associated with greater advantages in executive brain functions (Marian & Spivey, 2003). The present study examined the potential advantage which bi- and multilingual individuals may have over mono-lingual individuals in a dual-task paradigm assessing concurrent verbal fluency and manual motor response. Whilst previous research has demonstrated an advantage for bilingual individuals vs. monolinguals, less research has been conducted to explore any further advantage which may be found in multilingual individuals (those who fluently speak more than two languages). Furthermore, we required participants to carry out the manual motor component of the dual task twice, using each hand, as a proxy measure to explore possible neuroanatomical explanations (i.e., differential lateralisation) for such advantages.

Bilingualism, cognitive abilities, and verbal fluency

Executive functioning refers to the coordination of several complex cognitive processes and sub-processes (e.g., working memory, task-switching, inhibition, planning and execution), and takes place in the frontal cortex, predominantly (Alvarez & Emory, 2006; Elliott, 2003). Early evidence reported bilinguals to perform significantly better than monolinguals on various tests of cognitive ability and flexibility (e.g., Balkan, 1970; Cummins, 1978; Liedtke & Nelson, 1968; Peal & Lambert, 1962), however, more recently, cognitive advantages of bilingualism are extensively debated (see Antoniou, 2019). Advantages in these underlying cognitive abilities have been associated with an earlier age of language acquisition and greater language skill level (Birdsong, 2006); that is, the more proficient an individual is in the second language (L2), the better they should perform on cognitive tasks requiring executive functioning (Perani & Abutalebi, 2005; Stocco et al., 2014).

A large body of research considers whether advantages stem from increased inhibitory control, improved selective attention, or a combination of both (see Bialystok et al., 2009; Bialystok, 2017 for detailed reviews). Despite the body of evidence suggesting that bilinguals benefit cognitively from knowledge of an additional language there are areas of processing, specifically linguistic processing, where it is suggested that they perform more poorly. Evidence from language production tasks, specifically tasks of verbal fluency, suggest that bilingual individuals consistently produce fewer words on a category-based verbal fluency task than monolingual counterparts (Bialystok et al., 2008a; Linck et al., 2009). Category-based fluency tasks require participants to name as many exemplar words as they can for a single category; however, in letter-based verbal fluency tests, where participants must name as many exemplars as they can, beginning with a single letter (and omitting additional variants of the root word), studies have shown no difference between bi- and mono-lingual participants (e.g., Rosselli et al., 2000). Further studies have shown that bilinguals produce words later into the time-window given to complete the task (Luo et al., 2010; Sandoval et al., 2010). Indeed, studies where vocabulary size was controlled demonstrated a bilingual advantage in the letter-based verbal fluency task (Bialystok et al., 2008b; Luo et al., 2010), suggesting that letter fluency tasks are more reliant on executive functions than other tasks of verbal fluency.

Dual-task paradigms and the speech motor network

A dual-task paradigm requires two tasks to be carried out concurrently and can be used to examine the attentional demands that one task may have on another (Pashler, 2000); for example, the effects of completing concurrent motor tasks on verbal fluency (e.g., Pashler, 1990). Dual-task paradigms assume that central processing resources must be divided between two tasks being completed at the same time, due to a limited processing capacity (Kahneman, 1973). Performance exhibited on cognitive tasks may depend on the demands imposed by the primary task; performance on the secondary task may be reflective of the individuals' remaining processing capacity (Abernethy, 1988). The dual-task paradigm, specifically the verbal-manual interference task, has been shown to require hemispheric involvement as evidenced by reduced motor performance (Dromey & Shim, 2008; Hellige & Kee, 1990; Kinsbourne & Hicks, 1983). The subsequent decline in dual-task performance in comparison to single task performance was referred to as the *dual-task decrement*, *dual-task effect*, or *performance decrement* (Della Salla et al., 1995; Hiscock, 1982; McDowell et al., 1997; Hodgson et al., 2019).

There is evidence to suggest that the neuroanatomical control of both fine motor movements and speech production are linked, and seated within the left hemisphere (Vingerhoets et al., 2013). This suggestion aligns with models of speech perception which assert that speech production is controlled by a dorsal stream critical for auditory-motor integration (e.g., Hickok & Poeppel, 2000). Dual-task paradigms have been used to examine the lateralisation of speech production (see Medland et al., 2002) and more recently used in conjunction with functional transcranial Doppler sonography (fTCD) to consider the concept of overlapping neural networks for speech production and motor movement, particularly hand movements (Hodgson et al., 2019). Hodgson et al. found that whilst both motor performance and speech were impaired in a dual-task paradigm, speech performance was more markedly affected. These authors argue that it is the common aspect of sequential processing relied upon by speech and fine motor movement which drives the activation of the left hemisphere during these activities (Flowers & Hudson, 2013).

Bilingual individuals have consistently been found to have advantages in challenging cognitive tasks, such as a dual-task condition. Previous research has examined the benefits of language experience on performance in dual task paradigms (see Green & Vaid 1986 for an early discussion). Bialystok (2011), for instance, found that bilingual children performed better than monolingual children when making perceptual judgements of visual or auditory stimuli. WhilstKornisch et al. (2016) explored the relationship between stuttering and bilingualism via a visual hemifield paradigm. They demonstrated a left visual field | right hemisphere advantage across bi- and mono-lingual participant groups for the processing of visual stimuli. However, both bilinguals who stutter and bilinguals who did not stutter showed better performance (faster reaction times, fewer errors) than monolinguals, suggesting that bilingualism might offset deficits in executive functioning. Kornisch et al. (2017) utilised a digital finger-tapping task, performed concurrently with two linguistic tasks, to explore hemispheric processing. Tapping 'handedness' was alternated across trials. Kornisch et al. (2017) found no differences between bilinguals who stutter and bilinguals who did not stutter in any measures. Bilinguals who stutter showed less dual-task decrement than monolinguals who stutter during simultaneous verbal counting + finger tapping (right hand). Based on their findings, Kornisch et al. argued that bilingualism could compensate for deficits in executive function found in people who stutter. Thus, bilinguals' advantageous performance in dual-task paradigms may be reflective of cognitive reserve, where the additional processing associated with greater language proficiency leads to brain networks with greater processing capacity (Stern, 2005; Tucker & Stern, 2011). Kornisch et al.'s key findings are limited to verbal counting (automatisms), rather than a lexical-semantic task. Furthermore, their sample was limited to bilingual German (L1) and English (L2) participants. We revisit the performance of mono-, bi-, and multilingual participants in a dual-task paradigm (i.e., concurrent verbal + motor tasks), with an entirely neurotypical sample.

Language lateralisation and multilingual processing

Behavioural studies using dual-task paradigms consistently report left-lateralisation of speech (e.g., Medland et al., 2002). One early model (Kinsbourne & Hicks, 1978), based on right-handed individuals, suggests that performance on simultaneous tasks varies inversely to the functional distance between the activation of different cerebral networks. Therefore, where language is left-lateralised, concurrent motor activity will cause greater interference with the right than left hand. More recent models, taking advantage of advances in neuroimaging, are still focused on anatomical proximity, and overlapping activation of brain areas implicated in speech and motor tasks. For example, Hickok and Poeppel (2000; see also 2004; 2007; Hickok, 2012) propose a dorsal stream, crucial for speech development which supports integration between auditory and motor representations of speech, likely to be strongly left-lateralised. Taken in conjunction with evidence from Hodgson and colleagues (Hodgson & Hudson, 2018; Hodgson et al., 2019), this research demonstrates the predominant left-lateralisation of speech production.

However, contrasting evidence suggests variability in lateralisation, particularly in relation to handedness. Demonstrations of left hemisphere language lateralisation in left-handed individuals are not as clear or compelling, suggesting that left-handers tend to be less language-lateralised (or potentially right-lateralised) than their right-handed counterparts (Knecht et al., 2000). A review of neuroimaging studies demonstrated the importance of right hemisphere contributions in language processing (Bernal & Ardila, 2014). Using fMRI, the right hemisphere was shown to play a key role in semantic word generation (Chiarello et al., 2006). Knecht et al. (2000) estimated right hemisphere language dominance in 27% of strong left-handers. Using functional transcranial Doppler sonography, they tested a sample of healthy individuals participating in a word-generation task and reported the likelihood of right hemisphere language dominance to increase with the degree of left-handedness.

Studies of language laterality have consistently found differences in hemispheric activation when tasks are performed in another language (i.e., not a participant’s native tongue). Using a dual-task paradigm involving finger-tapping and interpretation/paraphrasing Green et al. (1990) found bilinguals to be bilateralised in tasks of interpretation. DeLuca et al. (2019) conducted a review and found that neural organisation was shaped by the combined effects of both the duration and extent of (multiple) language use. In a meta-analysis Hull and Vaid (2006) found that adult cerebral language lateralisation reflects early learning of two languages with early bilinguals demonstrating bilateral hemispheric involvement in language tasks. Whilst Hull and Vaid (2007) suggested that the right hemisphere is differentially involved depending on language. These authors found that proficient bilinguals who learned their L2 in infancy (i.e., before the age of 5 years) showed greater bilateral representation of that second language than those who acquired L2 later. However, the convergence hypothesis (Green, 2003) predicts that as linguistic proficiency increases, the neuroanatomical substrates underpinning both L1 and L2 assimilate (n.b., this hypothesis does not explicitly attend to the issue of lateralisation, per se). Gurunandan et al. (2020) showed that for bilinguals performing production tasks, left lateralisation was evidenced for each language; however, in receptive tasks, participants' L1 and L2 languages were found to lateralise to opposing hemispheres, and this effect increased with participants' language proficiency.

Bishop et al. (2021) used fTCD to test their hypothesis that lateralisation is equivalent for first and second languages in proficient bilinguals. They conducted two studies – Study 1 involved French-English and German-English bilinguals, and the second involved Japanese-English bilinguals. In the first study, participants (typically young adults, right-handed, and highly proficient in their non-native English language) completed a cued word generation task (similar to Knecht et al., 1998) and consisted of 23 trials. Participants were instructed to silently generate their responses. The overwhelming majority of participants (92%) showed left-lateralisation for L1 (8% right), and L2 (88% left, 12% right), and laterality indices were highly similar across languages (Bishop et al., 2021). There was no evidence for an age of acquisition effect on laterality indices in L2 (Bishop et al., 2021).

Study 2 – conducted independently by different lead researchers than Study 1 – involved typically slightly older participants with wider range of proficiency scores in the non-native English language tasks than the first study. The word generation task in Bishop et al.'s (2021) second study was based on that of Gutierrez-Sigut et al. (2015) and demanded either phonological or semantic generations. Participants had 17 seconds in which to generate their responses overtly (out loud), in contrast to the task in Study 1. Data from Study 2 indicated greater bilateralisation than in Study 1. Phonological generation data suggested 72% left- and 28% bi-laterality in L1 and 76% left- and 20% and bi-laterality in L2 (with 4% right-laterality). Semantic generation data showed a similar pattern – 72% left- and 28% bi-laterality in L1 and 64% left- and 32% bi-laterality in L2 (with 4% right-laterality). Consistently, across both studies, Bishop et al. (2021) found no effect of age of acquisition on laterality indices, neither through tests of association nor through tests of difference between those with early and late L2 Age of acquisition.

Pillai et al. (2003) found significant right hemisphere activation in phonological tasks in a non-native language. Calabrese et al. (2001) showed right hemispheric prefrontal activation during a word-fluency paradigm in a second language. The additional recruitment of right hemisphere regions for speech in bi- and multilingual individuals suggests that interference between speech and hand motor movement areas within the bilingual brain may be more diffuse than for monolingual individuals.

The Current Study

The current study examined dual-task interference, using isolated and concurrent verbal fluency and manual motor tasks, with monolingual, bilingual, and multilingual participants. By asking participants to complete a verbal and manual motor task concurrently we can consider two types of dual-task decrement simultaneously to consider whether a trade-off naturally occurs where a primary task is not highlighted (e.g., Navon, 1990). We chose to divide individuals who were fluent in other languages into two groups: those who could speak a single additional language and those who can speak more than one additional language. In this way we aimed to test any additional benefits of increased language capability. For example, multilingual participants may have an increased (global) vocabulary which would in turn improve their performance on the verbal fluency task (Bialystok et al., 2008b; Luo et al., 2010). As the dual-task paradigm involves components of inhibition and selective attention it was expected that multilingual participants would perform better on concurrent tasks than bilingual participants, who in turn would perform better than monolingual participants. In line with previous research highlighting the proximity of neural networks for speech production and fine motor control (Hodgson et al., 2019), it was expected that monolingual participants would be more clearly impaired in concurrent tasks when performing motor activity right-handed, as opposed to left-handed. However, the expected pattern of effects for individuals with more-extensive language ability is less clear. As evidence suggests that cerebral networks for language processing in bi- and multilingual participants may be more diffusely organised, including additional recruitment of areas within the right hemisphere, the pattern of interference demonstrated by these participants on the dual-task may differ. We predicted that reduced reliance on solely left hemisphere areas for speech and language in bi- and multilingual participants may lead to reduced interference on concurrent tasks, regardless of the hand executing the task.

Method

Participants

Fifty right-handed adults (32 females, M_{age} = 22.06 years, *SD* = 3.98 years; aged 18-38 years old), educated to undergraduate level, and reporting no history of speech or language disorders, participated voluntarily. Eighteen participants were monolingual (9 males, 9 females; M_{age} = 22.17 years, *SD* = 3.99 years; 18-34 years), sixteen were bilingual (5 males, 11 females; M_{age} = 22.44 years, *SD* = 4.97 years; 19-38 years), and sixteen were multilingual (4 males, 12 females; M_{age} = 21.56 years, *SD* = 2.92 years; 18-30 years). All participants were native English speakers. Additional languages for bilingual and multilingual participants can be seen in Table 1.

Table 1. Participant language abilities by groups

Group	L1 (Native)	L2	L3	L4	L5
Monolingual	English (*n*=18)	--	--	--	--
Bilingual	English (*n*=16)	French (*n*=4)	--	--	--
		Gujarati (*n*=4)	--	--	--
		Hindi (*n*=3)	--	--	--
		Pahari (*n*=2)	--	--	--
		Bengali (*n*=1)	--	--	--
		Tamil (*n*=1)	--	--	--
		Urdu (*n*=1)	--	--	--
Multilingual	English (*n*=16)	Urdu (*n*=5)	Hindi (*n*=4)	French (*n*=1)	Spanish (*n*=1)
		French (*n*=3)	Urdu (*n*=4)	German (*n*=1)	Swedish (*n*=1)
		Punjabi (*n*=3)	Nepali (*n*=3)	Greek (*n*=1)	--
		Greek (*n*=2)	French (*n*=2)	Hindi (*n*=1)	--
		Hindi (*n*=2)	Pahari (*n*=2)	--	--
		Twi (*n*=1)	Spanish (*n*=1)	--	--

Design and Materials

The Controlled Oral Word Association Test (COWAT; Benton & Hamsher, 1976), a subtest of the Multilingual Aphasia Examination, was used to assess verbal fluency via a word generation task. This widely-used test of phonemic verbal fluency was used due to the increased challenge involved in the lexical search of phonetic words as opposed to semantically-based words. . All participants completed this task in English (L1) under three conditions: in isolation, with concurrent right hand motor activity and with concurrent left hand motor activity. The COWAT has previously been demonstrated to have strong interrater reliability (e.g., Abwender et al., 2001; Troyer et al., 1997) and modest test-retest reliability (e.g., Ross et al., 2007). See Procedure section for details of the administration of this test.

A Grooved Pegboard Test (Matthews & Kløve, 1964), similar to the Purdue Pegboard Test (Tiffin, 1968), was used to assess motor skill performance as a manipulative motor dexterity test requiring visual-motor coordination. It consisted of 25 round peg holes, in a 5 × 5 array, on a square wooden board. The corresponding metal pegs were held by a groove in the upper part of the pegboard. The participant's task was to place the pegs into the holes with their right or left hand depending on the condition under examination. The maximum score on this test was 25 per trial (participants completed the pegboard task once per hand in isolation, and once per hand under dual-task conditions). Participants were given a time limit of 60 seconds per trial to align with the test of verbal fluency. Participants completed this task under 4 conditions: in isolation with their right hand, in isolation with their left hand, concurrently with the verbal fluency task (right hand and left hand). The order of tasks within and across language groups was carefully counterbalanced – for details, please see our Procedure section. The Grooved Pegboard Test has been previously found to have good test-retest reliability (e.g., Ruff & Parker, 1993).

A revised short-form of the Edinburgh Handedness Inventory (EHI; Veale, 2014) was used to determine participants' right/left hand-dominance. The original full-form of the EHI (Oldfield, 1971) assessed 10 everyday activities; the short-form inventory consisted of only 4 of those 10 activities (*writing, throwing, toothbrush & spoon handling*), which have previously shown a high reliability, factor determinacy and correlation with scores on the original inventory (Veale, 2014). As a self-report measure, participants were required to indicate their hand preference on a five-point scale ranging from '*Always Right*' to '*Always*

Left', a strong preference to either hand is scored as two points whilst a week preference is scored as one. The following formula is then used to calculate laterality quotient: LQ = [(R – L)/(R+L) x 100]. The calculation of a laterality quotient classified participants as being either left, mixed or right-handed; a score of 100 would indicate a full right-hand dominance. A strong right-hand dominance was required in order to take part in the study. The mean score for participants in the current study was 92.75 (*SD* = 9.81), confirming that all participants had a strong right-hand dominance. The short form of the EHI has been found to have very good reliability and factor score determinacy (e.g., Veale, 2014).

Procedure

Full ethical approval, in line with the standards of the British Psychological Society (2018), was obtained from the Psychology Department ethics committee of the University of Bedfordshire. All participants completed the revised short-form of the EHI (Veale, 2014). After displaying a laterality score indicating strong right-hand dominance, participants self-listed languages they were fluent in, in order of dominance; the number of languages listed determined participant’s language ability classification of monolingual, bilingual or multilingual. Each participant took part in a total of three conditions. As an act of counterbalancing, half of each language ability group completed the manual motor task in isolation first, followed by verbal fluency in isolation, and then both simultaneously. The other half of each language group completed the verbal fluency task in isolation first, followed by the manual motor task and then both simultaneously. All participants were presented with verbal instructions (in English) and examples of the required tasks prior to completing each of the experimental conditions. The total number of correct responses were noted during tests of verbal fluency.

<u>Verbal fluency</u>

As per the COWAT (Benton & Hamsher, 1976), participants were instructed to vocalise as many words as possible beginning with a given letter, as fast as possible, excluding proper nouns. Participants were given a time limit of 60 seconds. The total number of correct responses were noted during the test and later validated through voice recordings. The letter '*C*' was given to participants during the isolated condition, followed by letters '*L*' and '*F*' during the simultaneous conditions. Any proper nouns and repeated root words with added pre-fixes and suffixes were not included in the total word count score.

Manual motor task performance

Each participant completed the motor task in isolation, initially with their dominant (right) hand, followed by their non-dominant (left) hand. They were presented with the pegboard and metal pegs and were shown how to place the pegs in the holes. Participants were instructed to place only one item at a time, as fast as possible, using only one hand. If an item were to be dropped, the participant was instructed to disregard it and continue. Participants then repeated this procedure whilst simultaneously performing the verbal fluency task.

Data Analysis

Following the work of Hodgson et al. (2019), we calculated a dual-task decrement (DTD) to determine the extent of interference across conditions. This was calculated for each outcome measure – verbal fluency (VF) and manual motor task (MMT) – as per Hodgson et al. (p.1105):

DTD Quotient = [(dual-task score – single-task score) / single task score] × 100

Negative DTD scores = poorer dual-task performance relative to single-task, positive DTD scores = better dual-task performance relative to single-task; the greater the distance of the

DTD from zero, the greater the discrepancy between dual- and single-task performances.

The independent and interactive effects of number of languages spoken, task outcome, and executing hand, we used the 'lme4' package in R (Bates et al., 2015; R Development Core Team, 2016; http://www.r-project.org). Optimal random effect structures were identified using forward model selection (see Barr et al., 2013; Matuschek et al., 2017). Fixed effects were tested using likelihood-ratio tests comparing full and reduced models (e.g., Ingram & Hand, 2020). The 'simr' package (Green et al., 2022) was used to estimate the power of models. Our main model was adequately powered for detecting fixed effects in isolation and as part of two-way interactions (power ≥.90). Given the challenges associated with post-hoc power analyses, the three-way interaction was considered via sensitivity analysis, following the work of, for example, Perugini et al. (2018) and Lakens (2021). With an α=.05, a conservative estimate of power at .80, and a sample size of 50, a sensitivity analysis in G*Power 3.1.9.2 suggested that we could legitimately detect a three-way interaction effect down to a value of f = 0.995. The 'MuMIn' package (Bartoń, 2022) was used to calculate pseudo-R^2 (R^2_c) for mixed effects models (Nakagawa et al., 2017) as a proxy of effect size – this was then manually converted into Cohen's f (Cohen, 1988). For interactions involving the number of languages spoken, the 'interactions package' (Long, 2021) was used to perform follow-up Johnson-Neyman analyses (Taylor et al., 2022). The 'phia' package (De Rosario-Martinez, 2015) was used to calculate follow-up comparisons for the task × executing hand interaction.

Results

Our models included random intercepts by-participants. Additional intercepts and / or slopes either failed to improve these models or resulted in convergence issues. Descriptive statistics based on DTD scores are presented in Table 2. Please note, that although our analyses included number of languages spoken as a continuous integer variable, for convenience, descriptive statistics are presented by-groups. Raw descriptive statistics and figures representing these can be seen in the Supplementary Material A.

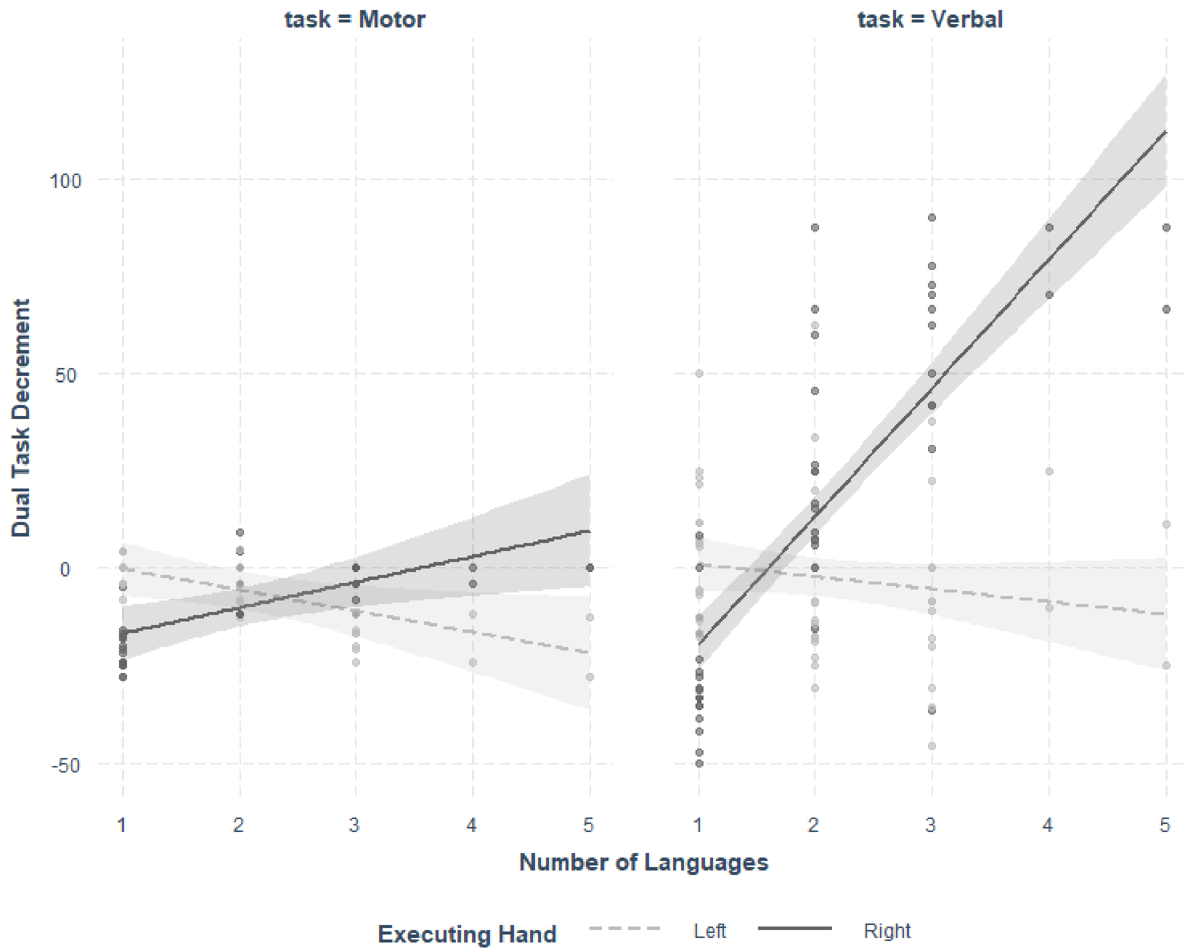
Table 2: Descriptive Statistics – Dual-Task Decrement

					95% CI	
Task	**Group**	**Hand**	**Mean**	**SE**	**Lower**	**Upper**
Verbal Fluency	Monolingual	Left	3.28	5.24	-7.28	13.83
		Right	-28.28	6.41	-41.17	-15.39
	Bilingual	Left	-4.31	5.56	-15.50	6.88
		Right	23.92	6.79	10.26	37.59
	Multilingual	Left	-7.32	5.56	-18.51	3.87
		Right	63.28	6.79	49.61	76.94
Manual Motor	Monolingual	Left	-1.29	1.38	-4.06	1.49
		Right	-21.22	1.31	-23.75	-18.47
	Bilingual	Left	-3.06	1.46	-6.00	-0.11
		Right	-3.45	1.39	-6.25	-0.65
	Multilingual	Left	-14.49	1.46	-17.44	-11.55
		Right	-3.00	1.39	-5.80	-0.20

Note. CI = Confidence Interval. SE = Standard Error. Monolingual n=18; Bilingual n=16; Multilingual n=16

There was a significant three-way interaction between, task, executing hand, and number of languages spoken [$\chi^2(1)=29.87$, $p<.001$; $R^2_c=.662$; Cohen's f = 1.283]; see Figure 1.

Figure 1. Three-way interaction with 95% confidence intervals for slopes.



Follow-up analysis revealed that motor DTD was influenced by number of languages spoken when the motor component of the dual-task was executed with either the left hand (t=-2.30, p=.02; Cohen's d=0.38) or the right hand (t=2.80, p=.01; Cohen's d=0.10). Verbal DTD was not influenced by number of languages spoken when the motor task was executed with the left hand (t=-1.36, p=.17); however, verbal DTD was significantly affected by the number of languages spoken when the motor component was executed by the right hand (t=13.90, p<.01; Cohen's d=5.43).

The three-way interaction was considered in terms of the effect of executing hand (as a proxy of hemispheric activity). Considering verbal DTD, the effect of motor component executing hand was significant regardless of how many languages were spoken, but the pattern of this effect differed. For monolinguals, verbal DTD was more-negatively impacted when the motor task was executed with the right hand (t=-4.49, p<.01; Cohen's d=1.82). For bilinguals, verbal DTD was more-negatively impacted when the motor task was executed with the left hand (t=5.82, p<.01; Cohen's d=1.18). For those speaking three or more languages, verbal DTD was more-negatively impacted when the motor task was executed with the left hand (t=12.67, p<.01; Cohen's d=3.20). In contrast, the pattern of effects of motor DTD was somewhat different. The effect of task executing hand on motor DTD was significant for monolinguals – motor DTD was more-negatively impacted when the motor task was executed with the right hand (t=-3.68, p<.01; Cohen's d=4.20). However, there was no significant effect of executing hand on motor DTD for bilingual participants (t=-1.16, p=.25) nor multilinguals (t=1.92, p=.06).

A summary of significant two-way interactions and individual fixed effects involving task, executing hand, and number of languages can be found in Supplementary Material B.

Discussion

The present study explored dual-task performance of participants who were either monolingual, bilingual, or multilingual, for isolated and concurrent verbal fluency (VF) and manual motor tasks (MMT). Our results show that the negative cost of dual-task performance was greater for the manual motor task than for the verbal fluency task we can assume that all participants have naturally treated the verbal task as the primary, trading-off performance in the manual motor task as a result. We have also found that the detrimental effects of performing dual tasks lessened as the number of languages spoken increased. That is, those able to speak more languages demonstrated a performance advantage in the motor component of the dual-task with both hands, and in the verbal component when completed with the right hand.

For monolingual participants verbal fluency DTD was more negatively impacted when the motor task was carried out with the right hand, whilst for bilingual and multilingual groups demonstrated a greater negative impact when the task was carried out with the left hand.

The overall effect of executing hand also differed between groups. Monolingual participants demonstrated greatest negative cost when carrying out the motor component with their right hand, whilst for bilingual and multilingual participants the negative cost associated with dual-tasking was least when the motor task was carried out with the right hand.

The present results from participants who were monolingual further support previous suggestions that verbal performance is more markedly impaired than motor performance in dual-task paradigms (Hodgson et al., 2019). However, the negative cost of dual-tasking on verbal performance diminished as the number of languages spoken increased, and both participants who were bilingual and multilingual demonstrated an advantage in measures of verbal fluency when using their right hand. Theories of cognitive reserve (Tucker & Stern, 2011) may provide an explanation for the different pattern in dual-task performance seen in these groups. That is, through practice of multiple languages, participants who speak multiple languages may have developed additional cognitive resources which reduce sensitivity to interference and allow for greater flexibility consequently leading to the observation of less detriment in dual tasks. This has been suggested in previous research which assessed concurrent verbal and manual motor activity (Kornisch et al., 2017). Our finding that the negative cost on verbal performance caused by dual-tasking diminished as the number of languages spoken increased, and, in fact, that multilingual participant demonstrated an advantage, may align further with this explanation; developing abilities in multiple languages may have led to the development of additional cognitive reserve. However, previously reported cognitive benefits of bilingualism (for a review see Bialystok et al., 2012) are now strongly debated (see Antoniou, 2019) and recent research suggests such advantages are not as robust as previously claimed (von Bastian et al., 2016).

Results also support older models of language lateralisation in showing a classic pattern of more pronounced dual-task decrement (Hiscock, 1982) for the monolingual participants. Kinsbourne and Hicks (1978) proposed the '*functional distance hypothesis*' (FDH), also referred to as the *cerebral space model*, which suggests that the performance on simultaneous tasks varies inversely to the functional distance between the activation of different cerebral networks. Kinsbourne and Hicks predict greater interference when a dual task involves speech and the right-hand, rather than speech and the left-hand. We may then postulate that participants with less left-lateralised language, for example bilinguals (as demonstrated by Bishop et al., 2021, Study 2) would be less affected when performing concurrent motor activity with the right hand.

The FDH may be useful for explaining the differential interference levels observed in dual-task paradigms, however the application of this theory to speech performance has not previously yielded strong supporting results (e.g., Dromey & Shim, 2008). Yet, the older model does align with more recent discussions of potential interference in overlapping neural networks of speech production and motor movement within the left hemisphere (Hodgson et al., 2019). In turn, this supports a model of speech perception where speech production is controlled by a stream integrating both auditory and motor function (Hickok & Poeppel, 2000). Our pattern of results can then be explained thus: as completing the tasks with the right hand is most taxing on the left hemisphere, with respect to the manual motor task it stands to reason that greater DTD would be seen in participants more reliant on this hemisphere. Bishop et al.'s (2021) results suggest a greater incidence of bi-lateral or right lateralised activity in bilingual participants. In turn, we have laid out results that demonstrate that those who speak multiple languages may demonstrate less interference, and some advantage, in right-handed concurrent tasks and more interference in left-handed concurrent tasks. It is possible that multilingual participants show less DTD with their right hand because they are recruiting additional neural resources for language, within the right hemisphere, aligning with early neuropsychological evidence that removing competition for processing mechanisms can have a beneficial effect on processing efficiency (Holtzman & Gazzaniga, 1985). As a result, they are then more impaired with the left hand as they engage brain areas which they have come to rely on for language.

As the present study is unable to discriminate the locus of neural activity during the dual tasks this result could also be accounted for by an integrated approach which suggests motor control would be facilitated by the proximity of speech and language areas of the brain. (Murphy & Peters, 1994). Spatially-separated regions of Broca's area have been found to be activated by both L1 and L2 (Kim et al., 1997), whilst a variation in activation of Broca's and Wernicke's areas have shown to increase with age of acquisition of L2 (Bloch et al., 2009). Multilingual participants who learned three languages successively rather than concurrently have displayed increased grey matter volume in language-associated cortical areas in both hemispheres (Kaiser et al., 2015). Consequently, in participants who learn L2, L3, and so on, later in life, the additional development of Broca's area leads to greater proximity of these areas to right hand motor areas which may, in turn, have facilitated performance (Murphy & Peters, 1994). However, this explanation can only account for facilitation of performance on right hand motor tasks seen in participants who were bi- and multilingual, and not for the poorer performance of participants who were multilingual with the left hand.

Whilst our results may suggest that the proximity of speech and motor brain regions underlies dual-task interference, there is also evidence for an advantage in verbal DTD based on number of languages spoken. As age of acquisition and skill level are indicators of advantages in cognitive abilities (Birdsong, 2006) and proficiency in L2 relates to performance on cognitive tasks (Perani & Abutalebi, 2005; Stocco et al., 2014). Bilingual language experience has been proposed to have a direct contribution on the brain's induced neuroplasticity, affecting the proportion of white matter structural changes, specifically within left-hemisphere brain regions (Khul et al., 2016), offering a comprehensive neurological explanation on the association of dual-task performance and bilingualism.

Linguistic distance (or dissimilarity in semantics or phonology) has also been proposed as a possible contributing factor (e.g., Wichmann et al., 2010) and may relate to advantages in executive function (Gollan et al., 2011), although evidence has been presented against this (see Sörman et al., 2019). Languages belonging to the same family, or those that exhibit greater semantic or phonetic overlap, may result in greater demands in the cognitive control system as opposed to linguistically distanced languages which could result in a lower degree of interference (Gollan et al., 2011; see also McMahon & McMahon, 2005). Several bi- and multilingual participants in the current study have L2 and L3 that would be classified as linguistically distant from their English L1, with a strong representation of Indo-Aryan languages (characterised by acoustic complexity). Zatorre et al. (2002) showed evidence of cortical asymmetries when processing auditory temporal (left) versus spectral (right) resolution. Speech comprehension has been proposed to engage left anterior temporal pathways (Scott et al., 2000). Acoustically-complex L2 or L3 languages that are linguistically-distant from L1 may result in differential involvement of the right hemisphere. Further research offering greater statistical power on both sample size and more extensive investigation of linguistic distance variation level would be necessary to evaluate this proposal.

The current study would potentially have benefited from quantifying the language abilities of the bi- and multilingual participants. Such task would undoubtedly require a great deal of effort, and 'decolonization' of assessment measures (Motha, 2020) to accommodate the diversity of global languages (also, clearer differentiation between dialects and languages). Moving forward, detailed assessment of language abilities and more-challenging tasks will help establish the extent to which participants who are multilingual have advantages in dual-task processing and executive functions. The COWAT may not represent the best test of verbal fluency for this research since the removal of proper nouns and repeated root words masks the total number of words generated, and could affect the motor DTD, an alternative test of verbal fluency should be considered. The study is limited in that verbal fluency is only tested in L1 and minimal data was collected on language history from bi- and multilingual participants. Further information such as age of acquisition, proficiency and type of language could be more systematically considered to provide a richer understanding of dual task interference in participants with differing language abilities. The current data set also does not allow us to consider the effects of task order on our results, order effects may have led to a reduction in the negative cost associated with dual-tasking in some conditions. Future research could also use fTCD to assess speech lateralisation following Hodgson et al. (2019).

In summary, participants with differing language abilities (monolingual, bilingual, or multilingual) demonstrated different patterns of dual-task interference when concurrently completing tasks of verbal fluency and manual motor control. These results provide support for the bi-lateralisation of language function in individuals able to speak more than one language. The separation of participants into groups of additional language ability, and the observation that those with greater language ability were less impaired on dual-tasks will further add to the literature in this area.

References

Abernethy, B. (1988). Dual-task methodology and motor skills research: Some applications and methodological constraints. *Journal of Human Movement Studies, 14*(3), 101-132.

Abwender, D.A., Swan, J.G., Bowerman, J.T., & S.W. Connolly (2001). Qualitative analysis of verbal fluency output: Review and comparison of several scoring methods. *Assessment*, *8*, pp. 323-336.

Alvarez, J.A., & Emory, E. (2006). Executive function and the frontal lobes: A meta-analytic review. *Neuropsychology Review, 16*(1), 17-42. https://doi.org/10.1007/s11065-006-9002-x

Antoniou, M. (2019). The advantages of bilingualism debate. *Annual Review of Linguistics, 5*, 395-415. https://doi.org/10.1146/annurev-linguistics-011718-011820

Balkan, L. (1970). *Les effets du bilinguisme francais-anglais sur les aptitudes intellectuelles*. Bruxelles: Aimav.

Barr, D.J., Levy, R., Scheepers, C., & Tily, H.J. (2013). Random effects structure for confirmatory hypothesis testing: Keep it maximal. *Journal of Memory and Language*, *68*(3), 255-278. https://doi.org/10.1016/j.jml.2012.11.001

Bartoń, K. (2022). Package 'MuMIn: Multi-Model Inference'. Accessed from: https://cran.r-project.org/package=MuMIn

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting Linear Mixed-Effects Models Using lme4. *Journal of Statistical Software*, *67*(1), 1-48. https://doi.org/10.18637/jss.v067.i01

Benton, A.L., & Hamsher, K. (1976). *Multilingual aphasia examination.* Iowa City: University of Iowa.

Bernal, B. & Ardila, A. (2014). Bilateral representation of language: A critical review and analysis of some unusual cases. *Journal of Neurolinguistics, 28*, 63-80. https://doi.org/10.1016/j.jneuroling.2013.10.002

Bialystok, E. (2001). *Bilingualism in Development: Language, Literacy, and Cognition.* Cambridge University Press: New York.

Bialystok, E. (2011). Reshaping the mind: the benefits of bilingualism. *Canadian journal of experimental psychology = Revue canadienne de psychologie experimentale, 65*(4), 229–235. https://doi.org/10.1037/a0025406

Bialystok, E. (2017). The bilingual adaptation: How minds accommodate experience. *Psychological Bulletin, 143*(3), 233–262. https://doi.org/10.1037/bul0000099

Bialystok, E., Craik, F.I.M., Luk, G. (2008a). Cognitive control and lexical access in younger and older bilinguals. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 34*, 859–873. https://doi.org/10.1037/0278-7393.34.4.859

Bialystok, E., Craik, F.I.M., Luk, G. (2008b). Lexical access in bilinguals: Effects of vocabulary size and executive control. *Journal of Neurolinguistics, 21*, 522–538. https://doi.org/10.1016/j.jneuroling.2007.07.001

Bialystok, E., Craik, F. I., & Luk, G. (2012). Bilingualism: consequences for mind and brain. *Trends in Cognitive Sciences, 16*(4), 240–250. https://doi.org/10.1016/j.tics.2012.03.001

Bialystok, E., Craik, F. I. M., Green, D. W., & Gollan, T. H. (2009). Bilingual Minds. *Psychological Science in the Public Interest, 10*(3), 89–129. https://doi.org/10.1177/1529100610387084

Birdsong, D. (2006). Age and second language acquisition and processing: A selective overview. *Language Learning*, *56*, 9-49. https://doi.org/10.1111/j.1467-9922.2006.00353

Bishop, D.V.M., Grabitz, C.R., Harte, S.C., Watkins, K.E., Sasaki, M., Gutierrez-Sigut, E., MacSweeney, Woodhead, Z.V.J., & Payne, H. (2021). Cerebral lateralisation of first and second languages in bilinguals assessed using functional transcranial Doppler ultrasound. *Wellcome Open Research, 1*(15). https://doi.org/10.12688/wellcomeopenres.9869.2

Bloch, C., Kaiser, A., Kuenzli, E., Zappatore, D., Haller, S., Franceschini, R., Luedi, G., Radue, E-W., & Nitsch, C. (2009). The age of second language acquisition determines the variability in activation elicited by narration in three languages in Broca's and Wernicke's area. *Neuropsychologia*, *47*(3), 625-633. https://doi.org/10.1016/j.neuropsychologia.2008.11.009

British Psychological Society (2018). *Code of Human Research Ethics*. Leicester: BPS.

Calabrese, P., Neufeld, H., Falk A., Markowitsch, H.J., Muller, C., Heuser, L., Gehlen, W., & Durwen, H.F. (2001) Word generation in bilinguals--fMRI study with implications for language and memory processes. *Fortschritte der Neurologie-psychiatrie*. *69*(1), 42-49. https://doi.org/10.1055/s-2001-10467

Cenoz, J. (2013). The influence of bilingualism on third language acquisition: Focus on multilingualism. *Language Teaching*, *46*(1), 1-16. https://doi.org/10.1017/S0261444811000218

Chiarello, C., Kacinik, N.A., Shears, C., Arambel, S.R., Halderman, L.K., & Robinson, C.S. (2006). Exploring cerebral asymmetries for the verb generation task. *Neuropsychology*, *20*, 88–104. https://doi.org/10.1037/0894-4105.20.1.88

Cohen, J. (1988). *Statistical Power Analysis for the Behavioral Sciences* (2nd Edition). New York: Routledge.

Cummins, J. (1978). Metalinguistic development of children in bilingual education programs: Data from Irish and Canadian (Ukrainian-English) programs. In M. Paradis (Ed.), *Aspects of bilingualism.* (pp. 127-138). Columbia, S.C.: Hornbeam Press.

De Rosario-Martinez, H. (2015). Package 'phia: post-hoc interaction analysis'. Accessed from: https://CRAN.R-project.org/package=phia

Della Sala, S. D., Baddeley, A., Papagno, C. & Spinnler, H. (1995). Dual-Task Paradigm: A Means to Examine the Central Executive. *Annals of the New York Academy of Sciences, 769*, 161–172. https://doi.org/10.1111/j.1749-6632.1995.tb38137.x

DeLuca, V., Rothman, J., Bialystok, E., & Pliatsikas, C. (2019). Redefining bilingualism as a spectrum of experiences that differentially affects brain structure and function. *Proceedings of the National Academy of Sciences*, *116*(15), 7565-7574. https://doi.org/10.1073/pnas.1811513116

Dromey, C., & Shim, E. (2008). The effects of divided attention on speech motor, verbal fluency, and manual task performance. *Journal of Speech, Language, and Hearing Research*, *51*, 1171-1182. https://doi.org/10.1044/1092-4388(2008/06-0221)

Elliott, R. (2003). Executive functions and their disorders. *British Medical Bulletin*, *65*, 49-59. https://doi.org/10.1093/bmb/65.1.49

Flowers, K. A., & Hudson, J. M. (2013). Motor laterality as an indicator of speech laterality. *Neuropsychology*, *27*(2), 256–265. https://doi.org/10.1037/a0031664

Gollan, T. H., Sandoval, T., and Salmon, D. P. (2011). Cross-language intrusion errors in aging bilinguals reveal the link between executive control and language selection. *Psychol. Sci.* 22, 1155–1164. https://doi.org/10.1177/0956797611417002

Green, A., Nicholson, N. S., Vaid, J., White, N. & Steiner, R. (1990). Hemispheric involvement in shadowing vs. interpretation: A time-sharing study of simultaneous interpreters with matched bilingual and monolingual controls. *Brain and Language, 39*(1), 107-133. https://doi.org/10.1016/0093-934X(90)90007-4

Green, A., & Vaid, J. (1986). Methodological issues in the use of the concurrent activities paradigm. *Brain and Cognition*, *5*(4), 465–476. https://doi.org/10.1016/0278-2626(86)90047-3

Green, D.W. (2003). Neural basis of lexicon and grammar in L2 acquisition: The convergence hypothesis. In Van Hout, R., Hulk, A., Kuiken, F., & Towell, R. (Eds). *The lexicon-syntax interface in second language acquisition.* John Benjamins.

Green, P., MacLeod, C., & Alday, P. (2022). Package 'simr: Power Analysis for Generalised Linear Mixed Models by Simulation'. Accessed from: https://cran.r-project.org/package=simr

Gurunandan, K., Arnaez-Telleria, J., Carreiras, M., & Paz-Alonso, P.M. (2020). Converging Evidence for Differential Specialization and Plasticity of Language Systems. *Journal of Neuroscience*, *40*(50), 9715-9724. https://doi.org/10.1523/JNEUROSCI.0851-20.2020

Gutierrez-Sigut, E., Payne, H., MacSweeney, M. (2015). Investigating language lateralization during phonological and semantic fluency tasks using functional transcranial Doppler sonography. *Laterality*, *20*(1), 49–68. https://doi.org/10.1080/1357650X.2014.914950

Hellige, J. B., & Kee, D. W. (1990). Asymmetric manual interference as an indicator of lateralized brain function. In G. R. Hammond (Ed.), *Advances in Psychology: Cerebral Control of Speech and Limb Movements*. Amsterdam, The Netherlands: Elsevier Science Publishers.

Hickok, G., (2012). The cortical organization of speech processing. *Journal of Communication Disorders*, *45*, 393-402. http://dx.doi.org/10.1016/j.jcomdis.2012.06.004

Hickok, G., & Poeppel, D. (2000). Towards a functional neuroanatomy of speech perception. *Trends in Cognitive Sciences*, *4*, 131–138. https://doi.org/10.1016/s1364-6613(00)01463-7

Hickok, G., & Poeppel, D. (2004). Dorsal and ventral streams: A framework for understanding aspects of the functional anatomy of language. *Cognition*, *92*, 67–99. https://doi.org/10.1016/j.cognition.2003.10.011

Hickok, G., & Poeppel, D. (2007). The cortical organization of speech processing. *Nature Reviews Neuroscience*, *8*, 393–402. https://doi.org/10.1038/nrn2113

Hiscock, M. (1982). Verbal-manual time sharing in children as a function of task priority. *Brain and Cognition*, *1*, 119-31.

Hodgson, J. C., & Hudson, J. M. (2018). Chapter 6 – speech lateralization and motor control. In G. S. Forrester,W. D. Hopkins, K. Hudry, & A. Lindell (Eds.), *Cerebral lateralization and cognition: Evolutionary and developmental investigations of behavioral biases* (Vol. 238, pp. 145-178). Elsevier. https://doi.org/10.1016/bs.pbr.2018.06.009

Hodgson, J. C., Tremlin, R., & Hudson, J. M. (2019). Disrupting the speech motor network: Exploring hemispheric specialization for verbal and manual sequencing using a dual-task approach. *Neuropsychology*, *33*(8), 1101–1110. https://doi.org/10.1037/neu0000589

Holtzman, J. D., & Gazzaniga, M. S. (1985). Enhanced dual task performance following corpus commissurotomy in humans. *Neuropsychologia*, *23*(3), 315–321. https://doi.org/10.1016/0028-3932(85)90018-1

Hull, R., & Vaid, J. (2006). Laterality and language experience. *Laterality: Asymmetries of Body, Brain and Cognition*, *11*(5), 436–464. https://doi.org/10.1080/13576500600691162

Hull, R., & Vaid, J. (2007). Bilingual language lateralization: a meta-analytic tale of two hemispheres. *Neuropsychologia*, *45*(9), 1987–2008. https://doi.org/10.1016/j.neuropsychologia.2007.03.002

Ingram, J., & Hand, C.J. (2020). Words from the wizarding world: Fictional words, context, and domain knowledge. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *46*(11), 2179–2192. https://doi.org/10.1037/xlm0000946

Kahneman, D. (1973). *Attention and effort.* Englewood Cliffs, N.J.: Prentice Hall.

Kaiser, A., Eppenberger, L.S., Smieskova, R., Borgwardt, S., Kuenzli, E., Radue, E-W., Nitsch, C., & Bendfeldt, K. (2015). Age of second language acquisition in multilinguals has an impact on gray matter volume in language-associated brain areas. *Frontiers in Psychology, 6 (638)*, https://doi.org/10.3389/fpsyg.2015.00638

Kuhl, P.K., Stevenson, J., Corrigan, N.M., van den Bosch, J J.F., Can, D.D., Richards, T. (2016). Neuroimaging of the bilingual brain: Structural brain correlates of listening and speaking in a second language. Brain and Language. Volume 162, Pages 1-9, ISSN 0093-934X, https://doi.org/10.1016/j.bandl.2016.07.004

Kinsbourne, M., & Hicks, R. E. (1978). Functional cerebral space: a model for overflow, transfer, and interference effects in human performance. A tutorial. In J. Requin (Ed.), *Attention and performance VII.* Hillsdale, NJ: Erlbaum. (pp. 345-362).

Kim, K.H.S., Relkin, N.R., Lee, K-M., & Hirsch, J. (1997). Distinct cortical areas associated with native and second languages. *Nature, 388*, 171-174. https://doi.org/10.1038/40623

Knecht, S., Deppe, M., Ringelstein, E.-B., Wirtz, M., Lohmann, H., Dräger, B., Huber, T., & Henningsen, H. (1998). Reproducibility of Functional Transcranial Doppler Sonography in Determining Hemispheric Language Lateralization. *Stroke*, *29*, 1155–1159. https://doi.org/10.1161/01.STR.29.6.1155

Knecht, S., Dräger, B., Deppe, M., Bobe, L., Lohmann, H., Flöel, A., Ringelstein, E.B., & Henningsen, H. (2000). Handedness and hemispheric language dominance in healthy humans. *Brain*, *123*(12), 2512-2518. https://doi.org/10.1093/brain/123.12.2512

Kornisch, M., Robb, M. P., & Jones, R. D. (2016). Estimates of functional cerebral hemispheric differences in monolingual and bilingual people who stutter: Visual hemifield paradigm. *Clinical Linguistics & Phonetics*, *31*(4), 251–265. https://doi.org/10.1080/02699206.2016.1240236

Kornsich, M., Robb, M. P., & Jones, R. D. (2017). Estimates of functional cerebral hemispheric differences in monolingual and bilingual people who stutter: Dual-task paradigm. *Clinical Linguistics and Phonetics*, *31*(6), 409.423. https://doi.org/10.1080/02699206.2017.1305448

Lakens, D. (2021). *Sample Size Justification*. https://doi.org/10.31234/osf.io/9d3yf

Linck, J.A., Kroll, J.F., Sunderman, G. (2009). Losing access to the native language while immersed in a second language. *Psychological Science*, *20*, 1507–1515. https://doi.org/10.1111/j.1467-9280.2009.02480.x

Liedtke, W. W., & Nebon. L. D. (1968). Concept formation and bilingualism. *Alberta Journal of Educational Research*, *14*. 225-232.

Long, J.A. (2021). Package ‘interactions: Comprehensive, User-Friendly Toolkit for Probing Interactions’. Accessed from: https://cran.r-project.org/package=interactions

Luo, L., Luk, G., Bialystok, E. (2010). Effect of language proficiency and executive control on verbal fluency performance in bilinguals. *Cognition*, *114*, 29–41. https://doi.org/10.1016/j.cognition.2009.08.014

Matthews, C.G., & Kløve, H. (1964). *Instruction manual for the Adult Neuropsychology Test Battery*. Madison, WI: University of Wisconsin Medical School

Marian, V., & Spivey, M. (2003). Competing activation in bilingual language processing: Within- and between-language competition. *Bilingualism: Language and Cognition, 6*(2), 97-115. https://doi.org/10.1017/S1366728903001068

Matuschek, H., Kliegl, R., Vasishth, S., Baayen, H., & Bates, D. (2017). Balancing Type I error and power in linear mixed models. *Journal of Memory and Language*, *94*, 305-315. https://doi.org/10.1016/j.jml.2017.01.001

McDowell, S., Whyte, J., & D'Esposito, M. (1997). Working memory impairments in traumatic brain injury: evidence from a dual-task paradigm. *Neuropsychologia*, *35*(10), 1341–1353. https://doi.org/10.1016/s0028-3932(97)00082-1

McMahon, A., and McMahon, R. (2005). *Language Classification by Numbers.* Oxford: Oxford University Press.

Medland, S.E., Geffen, G., & McFarland, K. (2002). Lateralization of speech production using verbal/manual dual tasks: meta-analysis of sex differences and practice effects. *Neuropsychologia*, *40*, 1233-1239. https://doi.org/10.1016/S0028-3932(01)00228-7

Motha, S. (2020). Is an Antiracist and Decolonizing Applied Linguistics Possible? *Annual Review of Applied Linguistics, 40*, 128-133. https://doi.org10.1017/S0267190520000100

Murphy, K., & Peters, M. (1994). Right-handers and left-handers show differences and important similarities in task integration when performing manual and vocal tasks concurrently. *Neuropsychologia, 32*(6), 663-674. https://doi.org/10.1016/0028-3932(94)90027-2

Nakagawa, S., Johnson, P.C.D., Schielzeth, H. (2017) The coefficient of determination R^2 and intraclass correlation coefficient from generalized linear mixed-effects models revisited and expanded. *J. R. Soc. Interface, 14*. 20170213.

Navon, D. (1990). Exploring two methods for estimating performance tradeoff. *Bulletin of the Psychonomic Society, 28*(2), 155–157. https://doi.org/10.3758/BF03333992

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

Pashler, H. (1990). Do response modality effects support multiprocessor models of divided attention? *Journal of Experimental Psychology: Human Perception and Performance, 16*, 826-840. Retrieved from: https://pubmed.ncbi.nlm.nih.gov/2148595/

Pashler, H. (2000). Task switching and multitask performance. In Monsell, S., and Driver, J. (editors). *Attention and Performance XVIII: Control of mental processes*. Cambridge, MA: MIT Press.

Peal. E., & Lambert, M. (1962) The relation of bilingualism to intelligence. *Psychological Monographs*, *76*(546). 1-23.

Perani, D., & Abutalebi, J. (2005). The neural basis of first and second language processing. *Current Opinion in Neurobiology, 15*(2), 202-206. https://doi.org/10.1016/j.conb.2005.03.007

Perugini, M., Gallucci, M., & Costantini, G. (2018). A practical primer to power analysis for simple experimental designs. *International Review of Social Psychology, 31*(1), 20. http://doi.org/10.5334/irsp.181

Pillai, J.J., Araque, J.M., Allison, J.D., Sethuraman, S., Loring, D.W., Thiruvaiyaru, D., Ison, C.B., Balan, A., & Lavin, T. (2003). Functional MRI study of semantic and phonological language processing in bilingual subjects: preliminary findings. *Neuroimage 19*, 565–576. https://doi.org/10.1016/s1053-8119(03)00151-4

Ross, T. P., Calhoun, E., Cox, T., Wenner, C., Kono, W., & Pleasant, M. (2007). The reliability and validity of qualitative scores for the Controlled Oral Word Association Test. *Archives of Clinical Neuropsychology, 22*(4), 475-488. https://doi.org/10.1016/j.acn.2007.01.026

Rosselli, M., Ardila , A., Araujo, K., Weekes, V. A., Caracciolo, V., Padilla, M & Ostrosky-Solí, F. (2000). Verbal fluency and repetition skills in healthy older Spanish-English bilinguals, *Applied Neuropsychology, 7*(1), 17-24, https://doi.org/10.1207/S15324826AN0701_3

Ruff, R. M., & Parker, S. B. (1993). Gender- and Age-Specific Changes in Motor Speed and Eye-Hand Coordination in Adults: Normative Values for the Finger Tapping and Grooved Pegboard Tests. Perceptual and Motor Skills, 76(3_suppl), 1219–1230. https://doi.org/10.2466/pms.1993.76.3c.1219

Sandoval, T.C., Gollan, T.H., Ferreira, V.S., Salmon, D.P. (2010). What causes the bilingual disadvantage in verbal fluency: The dual-task analogy. *Bilingualism: Language and Cognition, 13*, 231–252. https://doi.org/10.1017/S1366728909990514

Scott, S.K., Blank, C.C., Rosen, S., & Wise, R.J. (2000). Identification of a pathway for intelligible speech in the left temporal lobe. *Brain*, *123*(12), 2400-6. https://doi.org/10.1093/brain/123.12.2400

Sörman, D.E., Hansson, P. & Ljungberg, J.K. (2019) Different Features of Bilingualism in Relation to Executive Functioning, *Fronters in Psychology*, *10*(269). https://doi.org/0.3389/fpsyg.2019.00269

Stern, Y., Habeck, C., Moeller, J., Scarmeas, N., Anderson, K. E., Hilton, H. J.,. . . Van Heertum, R. (2005). Brain networks associated with cognitive reserve in healthy young and old adults. *Cerebral Cortex*, *15*(4), 394–402. https://doi.org/10.1093/cercor/bhh142

Stevens, J. (1996). *Applied multivariate statistics for the social sciences* (4th ed). Mahwah: Lawrence Erlbaum.

Stocco, A., Yamasaki, B., Natalenko, R., & Prat, C.S. (2014). Bilingual brain training: A neurobiological framework of how bilingual experience improves executive function. *International Journal of Bilingualism*, *18*(1), 67–92. https://doi.org/10.1177/1367006912456617

Taylor, H., Hand, C.J., Howman, H., & Filik, R. (2022). Autism, Attachment, and Alexithymia: Investigating Emoji Comprehension. *International Journal of Human–Computer Interaction*, https://doi.org/10.1080/10447318.2022.2154890

Tiffin, J. (1968). *Purdue pegboard: Examiner manual.* Chicago: Science Research Associates.

Troyer, A.K., Moscovich, M., & Winocur, G. (1997). Clustering and switching as two components of verbal fluency: Evidence from younger and older healthy adults. *Neuropsychology*, *11*, pp. 138-146

Tucker, A. M., & Stern, Y. (2011). Cognitive reserve in aging. *Current Alzheimer Research*, *8*(4), 354–360. https://doi.org/10.2174/156720511795745320

Veale, J.F. (2014). Edinburgh Handedness Inventory - Short Form: a revised version based on confirmatory factor analysis. *Laterality*, *19*(2), 164-177. https://doi.org/10.1080/1357650X.2013.783045

Vingerhoets, G., Alderweireldt, A. S., Vandemaele, P., Cai, Q., Van der Haegen, L., Brysbaert, M., & Achten, E. (2013). Praxis and language are linked: Evidence from co-lateralization in individuals with atypical language dominance. *Cortex, 49*, 172–183. http://dx.doi.org/10.1016/j.cortex.2011.11.003

von Bastian, C. C., Souza, A. S., & Gade, M. (2016). No evidence for bilingual cognitive advantages: A test of four hypotheses. *Journal of Experimental Psychology: General, 145*(2), 246–258. https://doi.org/10.1037/xge0000120

Wichmann, S., Holman, E. W., Bakker, D., and Brown, C. H. (2010). Evaluating linguistic distance measures. *Physica A* 389, 3632–3639. https://doi.org/10.1016/j.physa.2010.05.011

Zatorre, R.J., Belin, P., & Penhune, V.B. (2002). Structure and function of auditory cortex: music and speech. *TRENDS in Cognitive Sciences, 6*(1), 37-46. https://doi.org/10.1016/S1364-6613(00)01816-7

Data Availability

The data for the study are available at https://doi.org/10.17605/OSF.IO/2698J