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Estimates of functional cerebral hemispheric differences in monolingual and bilingual people who stutter: Dual-task paradigm

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ABSTRACT
The inter-relationship of stuttering and bilingualism to functional cerebral hemispheric processing was examined on a dual-task paradigm. Eighty native German (L1) speakers, half of whom were sequential bilinguals (L2 = English), were recruited. The participants (mean age = 38.9 years) were organised into four different groups according to speech status and language ability: 20 bilinguals who stutter (BWS), 20 monolinguals who stutter (MWS), 20 bilinguals who do not stutter (BWNS), and 20 monolinguals who do not stutter (MWNS). All participants completed a dual-task paradigm involving simultaneous speaking and finger tapping. No performance differences between BWS and BWNS were found. In contrast, MWS showed greater dual-task interference compared to BWS and MWNS, as well as greater right- than left-hand disruption. A prevailing finding was that bilingualism seems to offset deficits in executive functioning associated with stuttering. Cognitive reserve may have been reflected in the present study, resulting in a bilingual advantage.

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Introduction

Dual-task paradigms are utilised to assess performance of the two cerebral hemispheres via behavioural responses on cognitive, perceptual and motor tasks (Kinsbourne & Hiscock, 1983). The dual-task paradigm, such as the verbal-manual interference task, is a production-based paradigm and reflects hemispheric involvement as evidenced by decreased motor performance (Hellige & Kee, 1990). According to Kinsbourne and Hiscock (1983), the language-dominant left hemisphere is required to simultaneously and efficiently control speech and perform movements of the contralateral (right) hand. An asymmetric decrease in finger-tapping performance for the right hand indicates a lack of processing resources of the left cerebral hemisphere. Kahneman (1973) referred to this type of interference as ‘capacity interference’, and Norman and Bobrow (1975) hypothesised that it reflects limitations in the availability of cognitive processing capacity, resources and/or attention.

A prerequisite of dual-task performance is to successfully divide attention between two activities while maintaining task-relevant information. This process is dependent on the executive function system, which controls complex cognitive processes, including

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inhibitory control, cognitive shifting and updating of information (Jurado & Rosselli, 2007; Miyake et al., 2000). The first component, inhibitory control, describes the ability to deliberately block interfering responses (Miyake et al., 2000). The second component, cognitive shifting, refers to the ability to attend to relevant information, to ignore irrelevant information and to flexibly shift attention between several tasks (Kiesel et al., 2010). The third component, updating, includes the monitoring and manipulation of information, as well as temporary storage, in working memory during cognitively challenging tasks (Baddeley, 2010; Miyake et al., 2000).

The executive control system is thought to have a close interrelationship with cognitive reserve and brain reserve (Grant, Dennis, & Li, 2014). That is, superior executive functions provide the foundation for enhanced cognitive reserve, and cognitive reserve is strengthened by brain reserve in terms of increased cortical integrity (white matter) and density (grey matter). According to Stern (2009), brain reserve refers to individual differences in brain structure, such as more neurons or synapses that may increase resilience to brain pathology. In contrast, cognitive reserve refers to individual differences in brain function such as better processing and task performance that may increase tolerance to brain pathology. There are two distinct aspects of cognitive reserve: (a) neural reserve and (b) neural compensation (Stern et al., 2005). Neural reserve refers to increased efficiency and/or capacity of existing functional neural resources (Steffener, Reuben, Rakitin, & Stern, 2011). Neural reserve is thought to reflect normal individual capacity differences in task performance and coping mechanisms. Higher neural reserve enables brain networks not only to be more efficient but also to recruit additional resources when faced with highly demanding tasks. This is consistent with several neuroimaging studies of healthy participants, which have reported recruitment of additional brain areas/networks following an increase in task difficulty (Glahn et al., 2002; Grady et al., 1996; Jansma, Ramsey, Coppola, & Kahn, 2000). In contrast, neural compensation refers to the recruitment of atypical additional functional resources (Steffener et al., 2011). Neural compensation is thought to reflect an alteration of brain networks due to the physiological effects of aging or brain pathology, resulting in a neural network that would typically not be activated by an healthy individual (Stern et al., 2005). Hence, the brain is required to compensate for the lack of resources by using altered networks whenever the level of difficulty increases in a task. An example of a difficult cognitive task is a dual-task paradigm.

A large body of research supports the notion of a bilingual advantage on cognitively challenging tasks (e.g. dual tasks), particularly with respect to inhibitory control and task switching (Adesope, Lavin, Thompson, & Ungerleider, 2010; Bialystok, Poarch, Luo, & Craik, 2014; Kroll & Bialystok, 2013). Definitions of bilingualism vary, but researchers have agreed on two common concepts related to bilingualism: (1) language proficiency and (2) language acquisition (Bialystok, 2001; Kessler, 1984; Miller, 1984; Romaine, 1989). Language proficiency has been found to vary across different languages, as well as the receptive and expressive language modalities (listening, speaking, reading and writing) (Roberts, 2011; Roberts & Shenker, 2007). Furthermore, two different types of second language acquisition have been identified, including simultaneous bilingualism and sequential bilingualism (Owens, 2008). Simultaneous (or early) bilingualism refers to two or more native languages (L1) learned from birth, whereas sequential (or late) bilingualism describes second language learning (L2) after a first language has already been mastered (Field, 2011). The bilingual advantage is assumed to be due to the constant language switching, which requires enhanced cognitive control (Rodriguez-Fornells, De Diego Balaguer, & Muente, 2006). Bilinguals are constantly required to switch from one language to another language and inhibit the language not in use. In addition, there is evidence that both languages are always active to some degree (Hoshino & Kroll, 2008; Spalek, Hoshino, Wu, Damian, & Thierry, 2014). Thus, with both languages active, bilinguals are not only required to focus their attention to the target language while inhibiting attention to the other language, but also to monitor the context in order to switch attention when the other language is needed (Bialystok, 2011a). Executive functions are constantly needed since bilingualism itself creates a dual-task situation (Poarch & Bialystok, 2015). Researchers have examined dual-task performance in bilinguals who do not stutter (BWNS) and found that they perform better than monolinguals who do not stutter (MWNS) (Bialystok, 2011a, 2011b; Bialystok, Craik, & Ruocco, 2006). Both children and adult BWNS demonstrate less task disruption and better task accuracy during dual tasks. For example, Bialystok (2011a) assessed monolingual and bilingual children on single-task and dual-task conditions that required semantic judgement of either visual or auditory stimuli. This classification task was dependent on the executive function system and included inhibitory control, attention shifting and working memory components. No group differences were found on the single task, but, on the more complex dual task, the bilingual group demonstrated increased task accuracy and outperformed the monolingual group.

Dual-task paradigms have also been considered in the evaluation of people who stutter. Results from these studies indicate that stuttering appears to have a negative effect on performance when engaging in cognitive challenging tasks that require executive functions (Bosshardt, 2002; Jones, Fox, & Jacewicz, 2012; Metten et al., 2011). Particularly, monolinguals who stutter (MWS) were found to experience difficulties with shifting attention from one task to another and dividing attention between several concurrent tasks (Bosshardt, 1999, 2002, 2006; Schwenk, Conture, & Walden, 2007; S. Smits-Bandstra & De Nil, 2007). For example, Sussman (1982) examined dual-task performance in MWS and MWNS. Concurrent finger tapping was used during visual tasks (imagine and track alphabet shapes, chimeric figure test) and verbal tasks (reading aloud, counting backwards). During the verbal tasks, the MWS group demonstrated greater finger-tapping disruption than the MWNS group. MWS also demonstrated both right- and left-hand tapping disruptions during concurrent verbal tasks, while MWNS demonstrated only right-hand tapping disruptions. Furthermore, it has been suggested that the speech fluency of MWS is more sensitive to interference from cognitively demanding dual tasks (Bosshardt, 2002; Metten et al., 2011). MWS have been found to be more vulnerable to interference from concurrent tasks and demonstrate poorer dual-task performance compared to MWNS (Bosshardt, Ballmer, & De Nil, 2002; Greiner, Fitzgerald, & Cooke, 1986; Jones et al., 2012; Saltuklaroglu, Teulings, & Robbins, 2009; Sarah Smits-Bandstra & De Nil, 2009; Sussman, 1982).

The combined influence of stuttering and bilingualism on dual-task performance has not been considered. Data are emerging on the effects of stuttering, as well as bilingualism, on the processing and production of language (Howell & Van Borsel, 2011; Kornisch, Robb, & Jones, 2016). Both MWS and BWNS appear to show divergent patterns in functional cerebral hemispheric processing compared to MWNS. Past reports of deficits in executive functions among MWS and enhanced executive functions among sequential BWNS present an interesting paradox in regard to bilinguals who stutter (BWS). That is, would BWS exhibit dual-task performance more similar to that of MWS or BWNS? Recently, Kornisch et al. (2016) assessed BWS, MWS, BWNS and MWNS on a visual hemifield paradigm. All participants completed a task involving selective identification of common objects simultaneously presented to both visual fields. Overall, a left visual field advantage (i.e. right hemisphere advantage) was observed across all groups, indicating superior processing capabilities of the right hemisphere over the left with respect to visual stimuli. However, both bilingual groups (BWS, BWNS) showed faster reaction times and fewer identification errors than the two monolingual groups (MWS, MWNS). A prevailing finding was that bilingualism seems to offset deficits in executive functioning associated with stuttering. The present study involved further examination of the participants in the Kornisch et al. (2016) study. Using a dual-task paradigm, we sought to assess functional cerebral hemispheric processing in BWS and MWS, as well as their fluent controls.

Method

Participants

Eighty right-handed native German (L1) speakers, half of whom were sequential bilinguals (L2 = English), were recruited in Germany.[1] The participants (mean age = 38.9 years) were organised into four different groups according to speech status and language ability: 20 sequential BWS, 20 MWS, 20 sequential BWNS and 20 MWNS. Each of the groups comprised 12 males and 8 females. The groups were controlled and matched for sex, age (± 5 years), speech status (stuttering vs. non-stuttering) and languages spoken. The participants' handedness was based on self-reports. Informed consent was obtained from each participant.

Selection criteria

Bilingualism

All bilingual participants were born and raised in Germany and spoke German as L1 (dominant language) and English as L2. English was learned in a formal school setting at the age of 10 (± 1 year) for 6 to 9 years, and participants reported to be using English on a regular basis. All participants completed a language history questionnaire (Li, Zhang, Tsai, & Puls, 2014) and a proficiency self-rating scale (Lim, Rickard Liow, Lincoln, Chan, & Onslow, 2008) in order to obtain an estimation of their English language proficiency and assign them as either monolingual or bilingual. The English proficiency self-rating scale ranged from 1 (no skills) to 10 (native-like skills), and each number represented a level of language competence. Brief descriptions were given of the English skills required to meet the criteria for a specific level of language competence. Also, the English proficiency self-rating scale was divided into listening, speaking, reading and writing. Each modality was rated separately since language competence varies across the expressive and receptive language modalities (Roberts & Shenker, 2007). In order to increase homogeneity of the

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[1] Prior to data collection, statistical power was determined to decide on an appropriate sample size. In consultation with a statistician, it was calculated that a minimum sample size of 16 participants per group was required.

bilingual group, only proficient participants with a self-rating of six or higher on all four language modalities were included in the study. A rating below '3' in all modalities was required to be considered monolingual.

Stuttering

All MWS and BWS were diagnosed with developmental stuttering by a qualified Speech-Language Pathologist. The BWS and MWS groups were balanced with respect to stuttering severity and amount of previous treatment. Prior to the assessment, participants were required to complete a stuttering history questionnaire, as well as a stuttering severity self-rating scale ranging from 1 (no stuttering) to 9 (severe stuttering) (O'Brian, Packman, & Onslow, 2004). The stuttering severity for the MWS and BWS groups ranged from 2 (mild) to 9 (severe). The mean stuttering severity was 3.5 (range = 2–7) for the BWS group and 4.1 (range = 2–9) for the MWS group with no significant difference between groups.

Dual-task paradigm

Two linguistic tasks were used concurrently with finger tapping to assess hemispheric processing for language production. Similar materials and procedure have been used previously in investigations assessing dual-task performance (Badzakova-Trajkov, Kirk, & Waldie, 2008; Furtado & Webster, 1991; Soares, 1984).

Stimuli and procedure

The dual-task test was developed in the software *Eclipse* and *Java 1.6* and was administered and digitally controlled on a 13-inch Apple MacBook Pro Notebook. Finger tapping was measured from the trackpad surface of a MacBook Pro. The first tap of the finger on the trackpad activated a 60-s interval timer, which counted the number of taps on each trial. During the testing, participants were required to sit with both hands placed on top of a table and to keep the forearm of the tapping hand in contact with the table top to prevent whole arm movements. The heel of the hand and all fingers except the index finger were rested on the top surface of the notebook. All participants were instructed to (1) not look at their hand while tapping, (2) keep their hand steady while tapping, (3) move only the index finger of the tapping hand and (4) always tap as fast as possible, while performing all language tasks at a normal speaking rate. The researcher provided a demonstration of the desired finger-tapping procedure to each participant prior to data collection. Also, participants were frequently reminded between tasks to tap as fast as possible on all trials.

A single task, consisting of rapid left finger-tapping and rapid right finger-tapping alone, was used to establish a tapping baseline for each hand. Two verbal dual tasks were employed, including concurrent finger tapping while (a) reading a German version of 'The Rainbow Passage' (Fairbanks, 1960) and (b) reciting automatisms (i.e. counting in German). The 'Rainbow Passage' was displayed on the computer screen for 60-s. Participants were required to read the passage presented to them aloud and as accurately as possible. For the reciting automatisms dual task, participants were required to recite integers aloud, upwards from '1', until 60-s had elapsed. Each task consisted of two trials. The tapping hand was alternated after each trial, which resulted in one trial for each hand. The tapping hand was altered after each trial in order to avoid fatigue of the hands. The participants were able to initiate the onset of each task by pressing the spacebar, with the first tap on the trackpad activating the 60-s interval timer on each trial. Test instructions were given verbally prior to the start of the assessment. Instructions were also displayed at the top centre of the screen, indicating which task was to be performed.

Order effects

There was intentionally no counterbalancing for order effects between the left and right hands, with all participants given the same sequence of the four tasks: left-hand tapping/reading, right-hand tapping/reading, left-hand tapping/counting and right-hand tapping/counting. This was done to reduce the number of participant and task variables, which could be explored simultaneously with sufficient statistical power.

Data analysis

Statistical analyses were undertaken using IBM SPSS Statistics 21. A lack of homogeneity in group variance and non-normally distributed data was found across each of the groups, and, hence, non-parametric statistics were used for all analyses. For all group comparisons, the Mann–Whitney U-Test was used to determine if there were differences in the reading and counting conditions between the four participant groups. An exact sampling distribution for U was used, with an alpha level of .05 (2-sided). For all task comparisons, Wilcoxon Signed Rank Tests were run to explore possible differences within and between reading and counting conditions depending on the tapping hand for the four participant groups. Asymptotic significances were used, with an alpha level of .05 (2-sided). The Hodges–Lehmann estimator, with a 95% lower and upper confidence interval (CI), was used to measure the effect size of the median differences between the groups and tasks. Spearman rank-order correlation coefficients (r_s) were computed to ascertain the relationship among the tasks and stuttering severity, as well as language modalities. Alpha levels of .05 were used (2-sided).

To analyse the data set, the percentage change in finger tapping for each hand during each concurrent task was computed. Each participant's finger-tapping rate for the left and right hand was measured relative to the single-task control finger-tapping conditions (baseline). The following formula was used:

$$\text{Per cent change score (per hand)} = \frac{No.taps\ single-task-No.\ taps\ dual-task}{No.\ taps\ single-task}$$

The same formula has been used previously to calculate percentage change in finger tapping (Simon & Sussman, 1987; Soares, 1984). A positive value indicates a decrement or disruption in tapping rate (i.e. concurrent tapping rate is slower than baseline tapping rate). Participants generally tap faster with their preferred hand. Reading rate or reading accuracy was not recorded. The following four scores were obtained: (1) per cent change score in tapping during reading and tapping with the left hand (PCS-RL), (2) per cent change score in tapping during reading and tapping with the right hand (PCS-RR), (3) per cent change score in tapping during counting and tapping with the left hand (PCS-CL) and (4) per cent change score in tapping during counting and tapping with the right hand (PCS-CR). Group means and medians were obtained for each group.

Results

The results obtained for each of the participant groups are displayed in Tables 1 and 2. The results are presented according to specific group and task comparisons.

MWS versus MWNS

The PCS-CR was greater in MWS (*Mdn* = 25%) than in MWNS (*Mdn* = 5%), $p = .012$, with a median difference of 16% (95% CI = 3%–34%). No significant differences were found between groups for the PCS-RL ($p = 1.000$), PCS-RR ($p = .242$) and PCS-CL ($p = .383$) conditions.

MWNS versus BWNS

The PCS-RL was greater in MWNS (*Mdn* = 9%) than in BWNS (*Mdn* = 4%), $\underline{p} = .014$, with a median difference of −7% (95% CI = 1%–29%). No significant differences were found between groups for the PCS-RR ($p = .201$), PCS-CL ($p = .414$) and PCS-CR ($p = .495$) conditions.

BWNS versus BWS

No significant differences were found between groups for the PCS-RL ($p = .091$), PCS-RR ($p = .265$), PCS-CL ($p = .174$) and PCS-CR ($p = .289$) conditions.

Table 1. Dual-task results for the MWS and MWNS groups.

	MWS				MWNS			
	PCS-RL (%)	PCS-RR (%)	PCS-CL (%)	PCS-CR (%)	PCS-RL (%)	PCS-RR (%)	PCS-CL (%)	PCS-CR (%)
Mean	13	21	14	33	20	18	14	13
SD	38	24	42	28	32	34	30	25
Median	11	17	15	25	9	11	5	5
Range	−102 to 81	−15 to 80	−118 to 71	−1 to 88	−39 to 90	−54 to 91	−41 to 91	−22 to 80

Note. PCS-RL: per cent change score – reading/finger tapping with left hand; *PCS-RR*: per cent change score – reading/finger tapping with right hand; *PCS-CL*: per cent change score – counting/finger tapping with left hand; *PCS-CR*: per cent change score – counting/finger tapping with right hand.

Table 2. Dual-task results for the BWS and BWNS groups.

	BWS				BWNS			
	PCS-RL (%)	PCS-RR (%)	PCS-CL (%)	PCS-CR (%)	PCS-RL (%)	PCS-RR (%)	PCS-CL (%)	PCS-CR (%)
Mean	9	10	15	8	3	6	8	12
SD	16	12	19	17	14	7	15	15
Median	10	14	9	7	4	6	5	8
Range	−22 to 59	−14 to 35	−5 to 81	−12 to 67	−26 to 42	−14 to 23	−15 to 5	−20 to 41

Note. PCS-RL: per cent change score – reading/finger tapping with left hand; *PCS-RR*: per cent change score – reading/finger tapping with right hand; *PCS-CL*: per cent change score – counting/finger tapping with left hand; *PCS-CR*: per cent change score – counting/finger tapping with right hand.

BWS versus MWS

The PCS-CR was greater in MWS (*Mdn* = 25%) than in BWS (*Mdn* = 7%), $p = .004$, with a median difference of −19% (95% CI = 6%–39%). No significant differences were found between groups for the PCS-RL ($p = .429$), PCS-RR ($p = .114$) and PCS-CL ($p = .565$) conditions.

PCS-RL versus PCS-RR

No significant differences were found between the PCS-RL and PCS-RR conditions for BWS ($p = .794$), BWNS ($p = .179$), MWS ($p = .370$) and MWNS ($p = .823$).

PCS-CL versus PCS-CR

For MWS, the PCS-CR (*Mdn* = 25%) was larger than the PCS-CL (*Mdn* = 15%), $p = .028$, with a median difference of 10% (95% CI = 1%–29%). No significant differences in tapping rate were found between the PCS-CL and PCS-CR conditions for BWS ($p = .179$), BWNS ($p = .332$) and MWNS ($p = .526$).

PCS-RL versus PCS-CL

No significant differences were found between the PCS-RL and PCS-CL conditions for BWS ($p = .654$), BWNS ($p = .247$), MWS ($p = .823$) and MWNS ($p = .627$).

PCS-RR versus PCS-CR

No significant differences were found between the PCS-RR and PCS-CR conditions for BWS ($p = .079$), BWNS ($p = .247$), MWS ($p = .218$) and MWNS ($p = .391$).

Correlation analysis

There was a small significant positive correlation between stuttering severity and the PCS-CL condition ($r_s = .33$, $p < .05$). Stuttering severity was not significantly correlated with the PCS-RL, PCS-RR and PCS-CR conditions. In contrast, all of the four language modalities (listening, speaking, reading and writing) were significantly negatively correlated with the PCS-RL ($r_s = -.30, -.28, -.30, -.30$, respectively, $p < .05$), PCS-RR ($r_s = -.28, -.27, -.29, -.26$, respectively, $p < .05$) and PCS-CR conditions ($r_s = -.29, -.28, -.32, -.27$, respectively, $p < .05$). There was no significant correlation with the PCS-CL condition.

Discussion

This is the first study to have explored performance of BWS on a dual-task paradigm. No differences in performance were found between the BWS and BWNS groups on any of the conditions. In contrast, the BWS group demonstrated less dual-task interference than the MWS group on the PCS-CR condition. On the same condition, the MWS group was also found (a) to perform poorer than the MWNS group and (b) showed more task disruption during the PCS-CR condition than the PCS-CL condition.

In the present study, MWS performed slower than MWNS and demonstrated more interruption during the verbal counting task when tapping with the right hand. The MWS group also exhibited a difference in tapping rate between the left and right hand. There was no such difference in the MWNS group. It should be noted that verbal counting is assumed to particularly interfere with regulation of the primary motor task as a consequence of an overlap of concurrent task demands (Andres, Seron, & Olivier, 2007). A range of functional imaging studies have indicated that number processing activates a frontoparietal cortical network that partly overlaps the one recruited for hand and finger movement control (Andres et al., 2007; Pesenti, Thioux, Seron, & De Volder, 2000; Piazza, Mechelli, Butterworth, & Price, 2002; Pinel, Piazza, Le Bihan, & Dehaene, 2004; Zago et al., 2001). Findings from Andres et al. (2007) indicated that hand motor circuits are affected every time that the motor task is associated with any ordered series (e.g. counting). These researchers proposed that counting tasks could involve the premotor cortex, located within the frontal lobe of the brain, because of its role in conditioning finger movements to internal and external clues. Hence, even in the absence of actual movements, finger counting could be planned at a premotor stage. This suggestion aligns with studies by Haslinger et al. (2002) and Kuhtz-Buschbeck et al. (2003) who found involvement of the premotor cortex for imagined finger movements. This may also account for the finding of no group differences on any of the reading tasks in the present study.

Several researchers have proposed that stuttering is linked to brain activation abnormalities in the left premotor cortex and the left motor cortex during both speech and non-speech conditions (Chang, Kenney, Loucks, & Ludlow, 2009; Neef, Hoang, Neef, Paulus, & Sommer, 2015; Neef et al., 2011). For example, Neef et al. (2015) found that speech-motor plans are mainly controlled in the left motor cortex in MWNS. Yet, speech-motor planning was found in both hemispheres among MWS. They argued that this reliance on the left motor cortex appears to be a main physiological component of fluent speech production in MWNS. The different activation pattern found in MWS might be associated with a weaker structural connectivity and altered interaction between speech-related cortical regions in the left hemisphere. This assertion is supported by a large body of research claiming that stuttering is a type of disconnection syndrome due to reduced white matter in the left hemisphere speech-relevant areas (Cai et al., 2014; Chang, Erickson, Ambrose, Hasegawa-Johnson, & Ludlow, 2008; Chang, Horwitz, Ostuni, Reynolds, & Ludlow, 2011; Sommer, Koch, Paulus, Weiller, & Buchel, 2002; Watkins, Smith, Davis, & Howell, 2008).

Due to the complexity of dual-task conditions, a great amount of information needs to be actively controlled and managed. Dual-task performance heavily depends on executive functions (Strobach, Salminen, Karbach, & Schubert, 2014), as well as hemispheric connections (Serrien, 2009). However, executive functions have been found to be impaired in MWS (Bosshardt, 2002; Eggers, De Nil, & Van Den Bergh, 2013; Jones et al., 2012), as have visuoperceptual and visuomotor functions (Jones, White, Lawson, & Anderson, 2002). Jones et al. (2012) confirmed that MWS tend to perform poorer on dual tasks. In addition, moments of stuttering have been found to typically increase under concurrent conditions (Bosshardt, 2002; Metten et al., 2011). Researchers have suggested that deficits in both intra-hemispheric competition and inter-hemispheric integration processes might be present in MWS (Forster & Webster, 2001; Greiner et al., 1986; Webster, 1990). Based on evidence of probable impaired left-hemisphere motor functions (Alm, Karlsson, Sundberg, & Axelson, 2013; Neef et al., 2015), it is assumed that the two motor-based tasks (finger tapping and speaking) used in the present study may have been taxing to the left hemisphere of the MWS participants. As a result, tapping rates were more interrupted in this particular group. This would also explain why the interruption was only found for the left but not right hemisphere. There was no significant correlation between stuttering severity and PCS-CR. However, a positive correlation was found for the PCS-CL condition, which is consistent with findings by Szelag et al. (1993), suggesting right hemisphere involvement in children with severe stuttering. This result might reflect a compensation mechanism of stuttering in the right hemisphere (Preibisch et al., 2003).

No prior study has explored performance of BWS on dual-task paradigms so the current results cannot be directly compared to past research. Compared to the results obtained for the present BWS group, it appears that the BWS and BWNS groups performed similarly on all conditions. This was also the case for the same group of participants in the previous study using a visual hemifield paradigm (Kornisch et al., 2016). Therefore, it appears that the influence of bilingualism had a greater impact on dual-task performance than the influence of stuttering. One possible explanation of this phenomenon might be found in the brain networks associated with cognitive reserve. The concept of cognitive reserve refers to the assumption that brain networks that are more efficient and flexible are also less likely to be sensitive to interference (Stern et al., 2005). Thus, individual processing differences might result in divergent forms of reserve against brain pathology or age-related changes (Steffener et al., 2011; Stern et al., 2005). The dual-task paradigm in the present study required time-sharing during concurrent activities (e.g. verbal and manual). It is likely that the MWS group was using neural compensation rather than neural reserve during dual-task performance. In contrast, the BWS group outperformed the MWS group and performed similar to the BWNS group. This might be due to bilinguals showing enhanced executive functioning, specifically with respect to executive control (Adesope et al., 2010; Bialystok et al., 2014; Kroll & Bialystok, 2013). Interestingly, there is a growing body of research suggesting that bilingualism contributes not only to executive functioning but also to cognitive reserve (Stern, 2009). For example, it has been claimed that the levels of mental activity in which bilinguals continuously engage might protect against some of the effects of aging and disorders (Fischer & Schweizer, 2014; Gold, Kim, Johnson, Kryscio, & Smith, 2013). Therefore, neural reserve may have been reflected in the dual-task performance of the BWS and BWNS groups, resulting in a bilingual advantage (Tucker & Stern, 2011).

The BWS group performed very similar to the BWNS and did not show any of the disadvantages encountered by the MWS (which were also outperformed by the MWNS), supporting the contention that developmental stuttering is more reflective of a speech-motor than language-based communication disorder. The results generally align with research that considers stuttering to be a result of a deficiency in speech-motor control functions (Alm et al., 2013; Belyk, Kraft, & Brown, 2015; Namasivayam & Van Lieshout, 2011; Neef et al., 2015; Peters, Hulstijn, & Van Lieshout, 2000). The decreased performance for the MWS group, with respect to executive functions, seems to be a result of long-term compensation of motor deficits rather than a causal factor of stuttering.

Finally, the present findings have implications for clinical practice, particularly the assessment and management of stuttering. The diagnosis of stuttering is typically confined to the collection of speech samples and determining the amount and types of disfluencies (Jani, Huckvale, & Howell, 2013; Lee, Robb, Ormond, & Blomgren, 2014). However, the executive control system may also contribute to the management of speech fluency (Bosshardt, 2002, 2006; Eichorn, Marton, Schwartz, Melara, & Pirutinsky, 2016; Maxfield et al., 2016; Metten et al., 2011; Nejati, Pouretemad, & Bahrami, 2013). Metten et al. (2011) observed an increase in stuttering during dual-task conditions, indicating that the increase in cognitive demands diverted resources required for speech production away. Executive function training (i.e. attention and inhibitory control) was found to decrease stuttering severity on dual-task conditions (Nejati et al., 2013). Integrating exercises that require executive functions (e.g. dual tasks) into intervention programs might assist patients during everyday life situation that often require multitasking. This approach may provide extra support to control and maintain fluent speech in situations where attentional resources are frequently diverted away from controlling fluency by the demands of other tasks. Therefore, the testing of executive function could be considered as an adjunct to traditional fluency assessment batteries to elicit more complete data on the cognitive abilities of people who stutter.

Declaration of interest

The authors report no conflicts of interest.

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