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Estimates of functional cerebral hemispheric differences in monolingual and bilingual people who stutter: Visual hemifield paradigm

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ABSTRACT
The relationship between stuttering and bilingualism to functional cerebral hemispheric processing was examined using a visual hemifield paradigm. Eighty native German speakers, half of whom were also proficient speakers of English as a second language (L2), were recruited. The participants were organised into four different groups according to speech status and language ability: 20 monolinguals who stutter, 20 bilinguals who stutter, 20 monolinguals who do not stutter, and 20 bilinguals who do not stutter. All participants completed a task involving selective identification of common objects simultaneously presented to both visual fields. Overall, an LVF advantage was observed across all groups with no significant group differences in regard to hemispheric asymmetry. However, both bilingual groups showed faster reaction times and fewer identification errors than the two monolingual groups. A prevailing finding was that bilingualism seems to offset deficits in executive functioning associated with stuttering. Hence, the results lend support to previous findings implicating the benefits of bilingualism.

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Introduction

Visual hemifield testing involves the simultaneous presentation of two different visual stimuli, one to the left and one to the right, of a central point at which the participant is fixating (Hunter & Brysbaert, 2008; Van Der Haegen, Cai, Seurinck, & Brysbaert, 2011). In this way, stimuli can be lateralised and presented to primarily one hemisphere (Springer & Deutsch, 1998). Due to the crossing of fibres in the optic chiasm, visual stimuli flashed in the left visual hemifield (LVF) project initially to the right cerebral hemisphere, and visual stimuli flashed in the right visual hemifield (RVF) project initially to the left cerebral hemisphere (Beaumont, 1983). This phenomenon is based on the fact that the optical projections from the retina to the visual cortex are arranged in such a manner that the light falling onto the nasal region of the retina of both eyes will project the stimuli contralateral (Hellige, Laeng, & Michimata, 2010; Hugdahl, 2013). It has been found that bilateral presentations of stimuli result in even larger processing asymmetry than unilateral presentations regardless of the type of stimuli (e.g. verbal) and type of processing (e.g. verbal or spatial) (Boles, 1994). Furthermore, it has been found that the presentation time of stimuli is an important aspect in the visual field advantage, and a reduction in maximum exposure to 150 ms is recommended (Bourne, 2006). In general,

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the majority of right-handed individuals present with an RVF advantage for the identification of language-related stimuli, and an LVF advantage for nonverbal visual stimuli (Springer & Deutsch, 1998).

However, visual hemifield studies have indicated divergent patterns of language processing in monolinguals who stutter (MWS) (Hand & Haynes, 1983; Johannsen & Victor, 1986; Moore, 1976; Rastatter & Dell, 1987b; Rastatter, McGuire, & Loren, 1988; Szelag, Garwarskakolek, Herman, & Stasiek, 1993). For example, Hand and Haynes (1983) compared MWS to monolinguals who do not stutter (MWNS) on a lexical decision task, collecting vocal and manual reaction times. In contrast to MWNS, the MWS presented with an LVF advantage and demonstrated slower reaction times for both vocal and manual responses. Although there has been considerable progress in terms of understanding stuttering, the etiology of the disorder remains unknown. The early suggestion that stuttering is a result of brain dysfunction (Orton & Travis, 1929) has received support from neuroimaging studies that have revealed functional and structural brain changes in MWS (De Nil et al., 2008; Van Borsel, Achten, Santens, Lahorte, & Voet, 2003; Wu et al., 1997). Specifically, MWS appear to recruit the right hemisphere, in addition to the left hemisphere, during language processing (Foundas, Corey, Hurley, & Heilman, 2004; Sussman, 1982).

Visual hemifield performance has also been assessed in the field of bilingualism (Evans, Workman, Mayer, & Crowley, 2002; Hausmann, Durmusoglu, Yazgan, & Gunturkun, 2004; Jonczyk, 2015). Although definitions of bilingualism vary, there are two general concepts related to bilingualism: (a) language proficiency, and (b) second language acquisition (Bialystok, 2001; Kessler, 1984; Miller, 1984; Romaine, 1989). Bilingualism is considered to be a continuum and proficiency in the two languages varies across the receptive (listening, reading) and expressive (speaking, writing) language modalities (Roberts, 2011; Roberts & Shenker, 2007). In addition, two major types of second language acquisition have been identified: simultaneous bilingualism and sequential bilingualism (Krashen, 1987; Owens, 2008). According to Field (2011), simultaneous (or early) bilingualism refers to individuals introduced to both languages from birth. Thus, languages are acquired at the same time and considered to be first or native languages (L1). In contrast, sequential bilingualism refers to individuals introduced to a second language (L2) after they have already mastered a first language, which is also known as late bilingualism. A number of studies have suggested that sequential bilinguals who do not stutter (BWNS) show a strong RVF advantage for linguistic stimuli on visual hemifield tasks, which indicates greater left hemispheric language processing (Beaton, Suller, & Workman, 2007; Peng & Wang, 2011; Workman, Brookman, Mayer, Rees, & Bellin, 2000). This finding is further supported by a meta-analysis by Hull and Vaid (2006) on 23 laterality studies that examined functional hemispheric asymmetry for language in MWNS and simultaneous and sequential BWNS adults. The variables assessed included (a) language experience (monolingual, bilingual), (b) experimental paradigm (visual hemifield presentation, dual task, dichotic listening), (c) onset of bilingualism (simultaneous, sequential), and (d) language proficiency. Overall, the meta-analysis revealed that simultaneous BWNS demonstrated greater bilateral hemispheric involvement, whereas MWNS and sequential BWNS were left hemisphere dominant. Moreover, further research has suggested that sequential BWNS show even greater left hemisphere reliance compared to MWNS on the aforementioned behavioural tests assessing functional cerebral hemispheric asymmetry (Hull & Vaid, 2007; Vaid, 1987).

In addition to differences in hemispheric asymmetry, researchers have also examined executive functions in the fields of developmental stuttering and bilingualism. Executive functions are considered to be a primary subcomponent of metacognition and refer to the management and control of complex cognitive processes, including inhibitory control, cognitive shifting and updating of information (Jurado & Rosselli, 2007; Miyake et al., 2000). According to Miyake et al. (2000), inhibitory control refers to the ability to deliberately block interfering responses. In contrast, cognitive shifting, also referred to as attention or task switching, describes the ability to shift between several tasks, attending to relevant information and ignoring irrelevant information (Kiesel et al., 2010). The third component, updating, refers to the constant monitoring and rapid addition or deletion of information in working memory (Miyake et al., 2000). Executive functions are thought to be mainly but not exclusively regulated by the prefrontal cortex (Alvarez & Emory, 2006). MWS have been shown to have slower reaction times in cognitive processing tasks compared to MWNS. In particular, differences in executive functions have been observed with respect to linguistic processing (Maxfield, Morris, Frisch, Morphew, & Constantine, 2015; Rastatter & Dell, 1987a), working memory (Bajaj, 2007; Bosshardt, 2002; Metten et al., 2011), as well as inhibitory control and attention (Eggers, De Nil, & Van Den Bergh, 2012, 2013; Heitmann, Asbjornsen, & Helland, 2004). In particular, MWS have been found to experience difficulties with dividing attention between several concurrent tasks (Bosshardt, 2002, 2006). In contrast, bilingualism appears to have a positive effect on performance when engaging in cognitive challenging activities, particularly with respect to inhibitory control and task switching (Adesope, Lavin, Thompson, & Ungerleider, 2010; Kroll & Bialystok, 2013; Soveri, Laine, Hamalainen, & Hugdahl, 2011). This bilingual advantage is presumed to be due to the constant practice with language switching, which requires a high degree of cognitive control since bilinguals are constantly required to (a) inhibit the language not in use and (b) switch from one language to another language (Rodriguez-Fornells, De Diego Balaguer, & Muente, 2006; Soveri, Rodriguez-Fornells, & Laine, 2011). This advantage has also been found for sequential bilinguals (Bak, Vega-Mendoza, & Sorace, 2014; Sullivan, Janus, Moreno, Astheimer, & Bialystok, 2014).

Most studies on stuttering have focused on MWS and have not taken into account proficiency in more than one language. However, data are emerging on the effects of stuttering, as well as bilingualism, on the processing and production of language (Howell & Van Borsel, 2011). Collectively, both MWS and BWNS appear to show divergent patterns in functional cerebral hemispheric processing compared to MWNS in regard to language lateralisation (Brown, Ingham, Ingham, Laird, & Fox, 2005; Choo, Robb, Dalrymple-Alford, Huckabee, & O'Beirne, 2010; Hull & Vaid, 2007), as well as on executive functions (Adesope et al., 2010; Bosshardt, 2006). Missing from research examining cerebral hemispheric processing in stuttering and bilingualism is a direct examination of bilinguals who stutter (BWS). Past reports of a spread of cerebral activation and deficits in executive functions among MWS and a reliance of left hemisphere activation and enhanced executive functions among sequential BWNS present an interesting paradox in regard to BWS. That is, would functional cerebral hemispheric processing in BWS be more reflective of MWS or BWNS? The present study sought to address this question using a visual hemifield paradigm.

Method

Participants

Eighty right-handed native German speakers were recruited in Germany.[1] The participants were 48 males and 32 females with a mean age of 38.9 years (range = 18–58 years). Participants were divided into four groups (12 males and 8 females per group): 20 sequential BWS, 20 MWS, 20 sequential BWNS and 20 MWNS. The four 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. Only sequential bilinguals, who spoke German as L1 and English as L2, were included in the present study. All bilingual participants were born and raised in Germany and spoke German as their dominant language. English was learned in a formal school setting at the age of 10 (±1 year) for 6–9 years. At the time of data collection, all participants reported to be using English on a regular basis in their professional life and/or their leisure time. Participants completed a language history questionnaire, which was adapted and slightly modified from Li, Zhang, Tsai and Puls (2014), in order to obtain an estimation of their English language proficiency and assign them as either monolingual or bilingual. The language history questionnaire included an English proficiency self-rating scale (Lim, Rickard Liow, Lincoln, Chan, & Onslow, 2008), ranging from 1 (*no skills*) to 10 (*native-like skills*). Each number represented a level of competence and came with a brief description of English language skills that were required to meet the criteria for a specific level. The English proficiency self-rating scale was divided into listening, speaking, reading and writing and each modality was rated separately. This was done as per Roberts and Shenker (2007), who noted that competence varies across the expressive and receptive language modalities. Moreover, in order to increase homogeneity of the bilingual group, only proficient participants with a self-rating of six or higher on all four language modalities, as well as five or more years of formal study of the English language, were included in the study. In order to be considered monolingual, participants needed a rating below '3' in all modalities. All people with a self-rating of four or five in any language modality were excluded to keep the monolingual and bilingual groups separated.

Stuttering. Each MWS and BWS was required to have had (a) developmental stuttering previously diagnosed by a qualified Speech-Language Pathologist and (b) no other communication disorder. The BWS and MWS groups were balanced with respect to stuttering severity and amount of previous treatment. All participants, except for two MWS, were in treatment at the time of their study participation or had received speech therapy in the past. Prior to the assessment, participants were also required to complete a stuttering history questionnaire, which included a stuttering severity self-rating scale ranging from 1 (*no stuttering*) to 9 (*severe stuttering*). The self-rating scale has been found to be a reliable clinical tool in research contexts to measure stuttering severity (Karimi, Jones, O'Brian, & Onslow, 2014; O'Brian, Packman, &

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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.

Onslow, 2004). The stutter 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.

Visual hemifield paradigm

A bilateral visual hemifield picture-naming task was used to assess hemispheric involvement for language processing. There are a number of methodological requirements for the development of a good visual hemifield paradigm to assess language dominance (Bourne, 2006). Based on those methodological considerations, Hunter and Brysbaert (2008) designed two visual hemifield experiments, which were confirmed in a concurrent fMRI-based validation study to reliably predict language lateralisation. Their visual hemifield paradigm was replicated and slightly modified in the present study. The current paradigm differed from Hunter and Brysbaert (2008) in regard to (a) stimuli presentation and (b) response collection. The present study was originally designed to present the visual stimuli for a duration of 200 ms. However, a decision was made to reduce stimuli exposure to 100 ms since pilot research found the task to be too easy for the participants (e.g. absence of errors). The second modification concerned the technique for response collection. The previous researchers used a vocal task, while the present study used a manual task. Considering that 50% of the present participants were people who stutter, and stuttering typically occurs on word onset or initial syllables of a word (Brown, 1945), a manual lexical decision response was thought to be most appropriate so as to avoid a distortion in the reaction time measure.

Stimuli and procedure

The visual hemifield paradigm consisted of five pictures as stimuli, all representing high-frequency monosyllabic words. The pictures were of a boat, tree, book, lamp and house (Figure 1). Each picture was displayed and named in German 16 times within the LVF and 16 times within the RVF, resulting in 160 pictures to be named in total. The visual hemifield test was developed with the software “Eclipse” and Java 1.6, and was administered and digitally controlled on a 13-inch Apple MacBook Pro Notebook. A specially designed software program was used to present the visual stimuli, analyse the responses and display the results.

Participants viewed a monitor at a distance of about 60 cm and initiated the onset of the task by pressing the spacebar on the keyboard. At the beginning of each trial, they were asked to fixate on a cross for 1000 ms in the centre of the screen. The fixation cross is illustrated in Figure 2 (panel A). The five line drawings were presented repeatedly in a randomised order and stayed on the screen for 100 ms each. As per Hunter and Brysbaert (2008), the pictures were presented at a visual angle of approximately 2° from fixation with the outer edge at approximately 11°. The presentation occurred in a bilateral fashion, such that one picture was presented in the LVF, while another was simultaneously presented in the RVF. Bilateral presentation was controlled in such a way that no matching pictures were displayed at the same time. The picture to be named was indicated by an arrow that was flashed in the fixation space simultaneously with the bilaterally presented pictures (Figure 2, panel B). This ensured midline fixation throughout the assessment, since the arrow gave the cue to which side to attend to in order to give a correct response. Participants were then

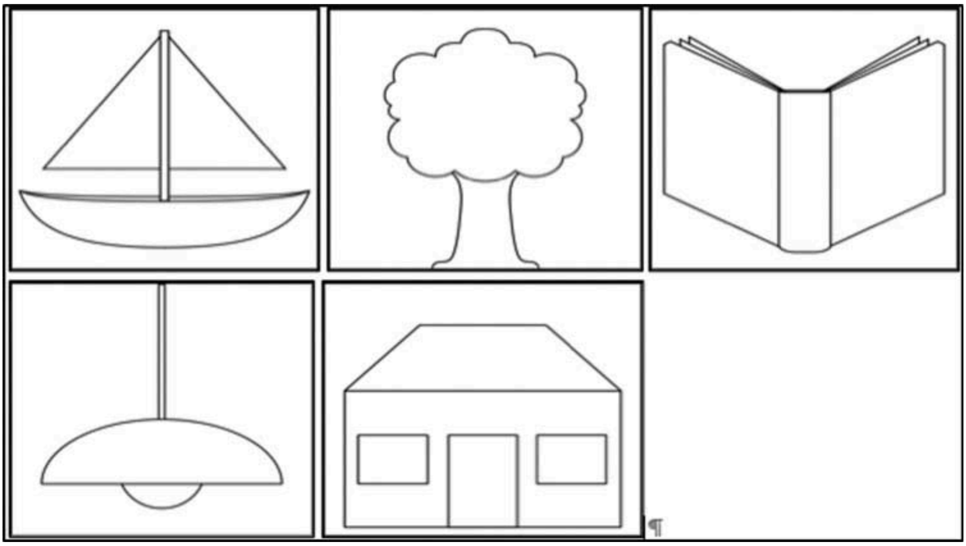

Figure 1. The five picture stimuli (boat, tree, book, lamp, house) used for the visual hemifield paradigm.

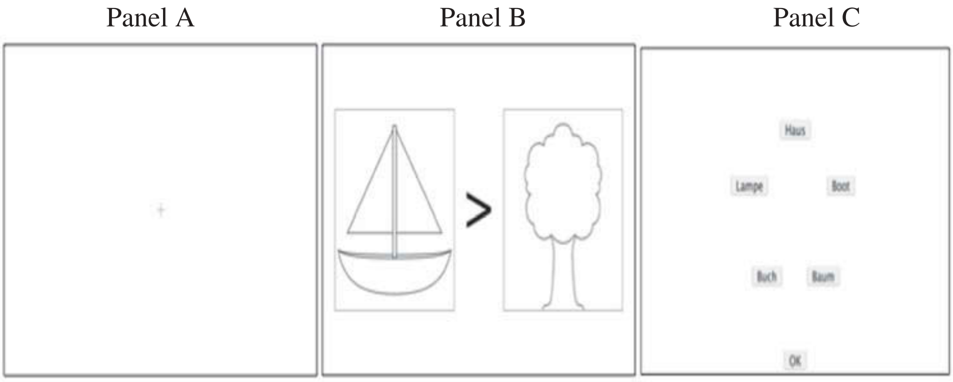

Figure 2. Sequence of visual hemifield testing beginning with a fixation cross (panel A), followed by stimuli presentation (panel B), and final response collection (panel C) for the visual hemifield paradigm.

required to select as quickly as possible the word that corresponded to the picture (Figure 2, panel C). The five words were arranged in a circle, with the computer mouse at the centre, and always appeared in the same order. Responses were collected by means of a mouse click, where the onset of the click was registered as reaction time for a specific stimulus. In case participants were not sure which picture they had seen, they were asked to guess when selecting the corresponding word. There were no breaks in this test but participants were able to decide for themselves when they were ready to continue to the next pictures by pressing ‘ok’. Once they had pressed ‘ok’, the next pictures followed immediately. The five pictures were shown to the participants beforehand to ensure familiarisation with the stimuli.

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. Accordingly, a decision was made to use non-parametric statistics for all analyses. The Mann–Whitney *U*-test was used to determine if there were differences in reaction time and error rate conditions between the four groups. An exact sampling distribution for *U* was 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. 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 (two-sided).

To analyse the data set, all identification errors were eliminated from the data, and mean reaction times were calculated for the LVF and RVF. Subsequently, the total number of errors was calculated for the LVF and RVF and mean values were obtained. A lateralisation index (LI) was derived for both reaction times and errors via the following formulae:

$$\text{LI for reaction time}(\text{RT}) = \text{RT for the LVF}(\text{RT\_LVF}) - \text{RT for the RVF}(\text{RT\_RVF})$$

$$\text{LI for errors}(\text{E}) = \text{Errors for the LVF}(\text{E\_LVF}) - \text{Errors for the RVF}(\text{E\_RVF})$$

This information was used to determine the visual hemifield (VHF) advantage of each participant for reaction times and errors. Negative LI values represented an LVF advantage and positive values represented an RVF advantage. Prior to statistical analysis, the data were normalised (1) due to non-normal distribution of data and (2) in order to rescale the data for group comparisons. The normalised differences (ND) for reaction time and errors were derived via

$$Normalized\ Difference = \frac{LVF - RVF}{\frac{(LVF + RVF)}{2}}$$

Absolute left–right differences for the LVF and RVF mean reaction times and mean errors were also considered. In total, eight scores were obtained in the visual hemifield paradigm: (1) VHF advantage for reaction time, (2) ND for reaction time, (3) LVF reaction time, (4) RVF reaction time, (5) VHF advantage for errors, (6) ND for errors, (7) LVF errors and (8) RVF errors. Group means and medians were obtained for each group.

Results

The results obtained for each of the participant groups are displayed in Tables 1–4, respectively. The results are presented according to specific group comparisons.

MWS and MWNS

No significant differences were found between groups for the LVF (p = .056), RVF (p = .063), VHF advantage (p = .779) and ND (p = .968) reaction time conditions. In contrast, the

Table 1. Visual hemifield results for the MWS group.

	Reaction time				Errors			
MWS	LVF (ms)	RVF (ms)	VHFA (ms)	ND (%)	LVF	RVF	VHFA	ND (%)
Mean	2160	2247	−87	−3	13	15	−2	−38
SD	561	572	146	6	12	13	6	74
Median	1989	2074	−45	−1	10	8	−2	−30
Range	1561 to 3584	1490 to 3644	−400 to 71	−17 to 4	0 to 52	2 to 44	−15 to 9	−200 to 72

Note. LVF: left visual field; RVF: right visual field; VHFA: visual hemifield advantage; ND: normalized difference.

Table 2. Visual hemifield results for the MWNS group.

	Reaction time				Errors			
MWNS	LVF (ms)	RVF (ms)	VHFA (ms)	ND (%)	LVF	RVF	VHFA	ND (%)
Mean	1863	1937	−74	−3	6	6	0	−44
SD	302	326	139	6	7	5	4	101
Median	1756	1833	−45	−2	3	3	−1	−53
Range	1461 to 2750	1404 to 2677	−402 to 90	−18 to 4	0 to 28	1 to 19	−9 to 10	−200 to 125

Note. LVF: left visual field; RVF: right visual field; VHFA: visual hemifield advantage; ND: normalized difference.

Table 3. Visual hemifield results for the BWS group.

	Reaction time				Errors			
BWS	LVF (ms)	RVF (ms)	VHFA (ms)	ND (%)	LVF	RVF	VHFA	ND (%)
Mean	1733	1849	−115	−6	4	7	−3	12
SD	263	332	138	6	5	17	18	116
Median	1756	1834	−90	−6	2	3	0	20
Range	1263 to 2422	1344 to 2880	−458 to 51	−18 to 2	0 to 22	0 to 80	−78 to 13	−190 to 200

Note. LVF: left visual field; RVF: right visual field; VHFA: visual hemifield advantage; ND: normalized difference.

Table 4. Visual hemifield results for the BWNS group.

	Reaction time				Errors			
BWNS	LVF (ms)	RVF (ms)	VHFA (ms)	ND (%)	LVF	RVF	VHFA	ND (%)
Mean	1654	1713	−59	−4	3	4	0	−7
SD	324	252	191	10	4	5	3	116
Median	1568	1642	−78	−5	2	3	−1	−12
Range	1261 to 2634	1348 to 2180	473 to 466	−24 to 19	0 to 18	0 to 21	−8 to 5	−200 to 200

Note. LVF: left visual field; RVF: right visual field; VHFA: visual hemifield advantage; ND: normalized difference.

number of RVF errors was higher in MWS (*Mdn* = 8 errors) than in MWNS (*Mdn* = 3 errors), $p = .009$, with a Hodges–Lehman median difference of 5 errors (95% CI = 1 error to 12 errors). No significant differences were found between groups for the LVF ($p = .060$), VHF advantage ($p = .142$) and ND ($p = .718$) error conditions.

MWNS and BWNS

The LVF reaction time was faster in BWNS (*Mdn* = 1568 ms) than in MWNS (*Mdn* = 1756 ms), $p = .009$, with a Hodges–Lehman median difference of −216 ms (95% CI = −381 ms to −53 ms). The same was found for the RVF reaction time, which was faster in BWNS (*Mdn* = 1642 ms) than in MWNS (*Mdn* = 1833 ms), $p = .024$, with a Hodges–Lehman median difference of −206 ms (95% CI = −393 ms to −34 ms). No significant differences were found between groups for the VHF advantage (p = .678) and ND (p = .602) reaction time conditions. No significant differences were found between groups for the LVF (p = .565), RVF (p = .398), VHF advantage (p = .698.) and ND (p = .369) error conditions.

BWNS and BWS

No significant differences were found between groups for the LVF (p = .166), RVF (p = .184), VHF advantage (p = .588) and ND (p = .708) reaction time conditions, or LVF (p = .968), RVF (p = .841), VHF advantage (p = .341) and ND (p = .547) error conditions.

BWS and MWS

The LVF reaction time was faster in BWS (*Mdn* = 1756 ms) than in MWS (*Mdn* = 1989 ms), p = .003, with a Hodges–Lehman median difference of −288 ms (95% CI = −534 ms to −108 ms). The same was found for the RVF reaction time, which was faster in BWS (*Mdn* = 1834 ms) than in MWS (*Mdn* = 2074 ms), p = .006, with a Hodges–Lehman median difference of −304 ms (95% CI = −618 ms to −84 ms). No significant differences were found between groups for the VHF advantage (p = .396) and ND (p = .270) reaction time conditions.

The LVF errors were lower in BWS (*Mdn* = 2 errors) than in MWS (*Mdn* = 10 errors), p = .023, with a Hodges–Lehman median difference of −7 errors (95% CI = −13 errors to −1 error). The same was found for the RVF errors, which were lower in BWS (*Mdn* = 3 errors) than in MWS (*Mdn* = 8 errors), p = .001, with a Hodges–Lehman median difference of −6 errors (95% CI = −13 errors to −2 errors). No significant differences were found between groups for the VHF advantage (p = .134) and ND (p = .108) error conditions.

Correlation analysis

Stuttering severity was not significantly correlated with any of the reaction time and error rate conditions. For the reaction time conditions, all four language modalities (listening, speaking, reading and writing) were significantly negatively correlated with LVF reaction time (r_s = −.40, −.42, −.42, −.41, respectively; $p < .01$) and RVF reaction time conditions (r_s = −.38, −.39, −.39, −.38, respectively; $p < .01$). For the error rate conditions, all four language modalities (listening, speaking, reading and writing) were significantly negatively correlated with the RVF errors condition (r_s = −.31, −.29, −.32, −.30, respectively; $p < .01$). In contrast, only the listening and reading modalities were significantly positively correlated with the ND for errors condition (r_s = .25, .24, respectively; $p < .05$), whereas the speaking and writing modalities were not significantly correlated with the ND for errors condition.

Discussion

Overall, an LVF advantage was observed across all groups with no significant group differences in regard to hemispheric asymmetry. All of the participants generally showed faster reaction times and fewer errors for stimuli presented to the LVF. Therefore, the current data appear to point to superior processing capabilities of the right hemisphere over the left with respect to visual stimuli. Several possibilities are presented for the lack of difference between groups. Findings of the present study are consistent with previous research suggesting a greater facilitation for concrete words in the right hemisphere (Rastatter & Dell, 1987b; Rastatter, Dell, McGuire, & Loren, 1987; Shibahara & Wagoner, 2002). Rastatter et al. (1987) found that reaction times were faster when concrete stimuli were presented to the LVF, whereas abstract stimuli were processed faster when presented to the RVF. This pattern has been noted in both MWS (Rastatter & Dell, 1987b) and MWNS (Shibahara & Wagoner, 2002) and indicates that language organisation might also be lexically dependent. Each hemisphere holds some level of linguistic competence and performance for certain types of linguistic information. Nevertheless, these results should be viewed with caution, especially in the light of a study by Fiebach and Friederici (2004), which provided fMRI evidence against a specific right hemisphere involvement in the processing of concrete words. More specifically, it was found that abstract words activated a subregion of the left inferior frontal gyrus (BA 45) more strongly than concrete words, whereas concrete words were in particular associated with activity in the left basal temporal cortex.

The visual hemifield paradigm used in the present study was inspired by the work of Hunter and Brysbaert (2008). However, the present findings do not parallel those obtained by these researchers. There are a number of methodological differences between the two studies that may account for the lack of agreement. The current study differed from Hunter and Brysbaert (2008) in regard to (a) stimuli presentation and (b) response collection. With respect to the decreased stimuli presentation, there may have been a trade-off between language processing and number of errors as a result of using a 100 ms stimulus duration. The rapid presentation of the stimuli may have prevented strong language processing in the RVF, resulting in slower reaction time and a larger number of errors. Instead, the right hemisphere was more capable of processing the rapidly displayed visual stimuli, resulting in faster and more accurate responses. With respect to the response collection, one could argue that use of a manual (compared to vocal) response might have influenced the present results. However, several studies have found a strong RVF advantage, i.e. left hemisphere processing, for the recognition of printed words (Bub & Lewine, 1988; Finkbeiner, Almeida, & Caramazza, 2006; Hunter & Brysbaert, 2008), which were used to collect the responses in the present study. Another major difference between the two studies is the participants' handedness. The participants sampled by Hunter and Brysbaert were all left-handed, whereas the participants from the current study were all right-handed. Presumably, the majority of right-handed participants would naturally present with dominant left hemisphere language (Pujol, Deus, Losilla, & Capdevila, 1999). In contrast, atypical bilateral or right hemisphere language lateralisation has been found to occur more often in left-handed participants (Pujol et al., 1999). The current study also assessed four different speaker groups, including people who stutter, whereas the former study only included one speaker group.

A further explanation for the LVF advantage demonstrated by the present groups might be attributed to the characteristics of the stimuli. The two cerebral hemispheres have been found to differ in their capacity to process information, with left hemisphere dominance for language processing and right hemisphere dominance for visuospatial processing and attention (Gotts et al., 2013; Hugdahl, 2011, 2013; Wang, Buckner, & Liu, 2014). The early work by Semmes (1968) indicated that the left hemisphere was more specialised for focal representations, while the right hemisphere was more specialised for diffuse representations. This concept is further supported by Gotts et al. (2013) who found two distinct patterns of functional lateralisation in the brain, establishing that the left and right cerebral hemispheres have qualitatively different biases in how they interact with each other. These researchers demonstrated a preference of the left hemisphere to interact more exclusively with itself, whereas the right hemisphere showed a stronger tendency to interact with both hemispheres. These two different forms of interaction were associated with left-dominant functions (i.e. language) and right-dominant functions (i.e. visuospatial attention) (Gotts et al., 2013). The stimuli in the present study were visual and highly attention-demanding followed by a linguistic decision task. As a result of this two-step procedure, the stimuli processing may have benefited more from the spatial connection of several synaptic inputs from both hemispheres and, thus, the integrative features of the right hemisphere provided a better and more effective match. This explanation is not only consistent with the fMRI data and proposal of Gotts et al. (2013) but also with a recent MEG study conducted by Doron, Bassett and Gazzaniga (2012), who concluded that interhemispheric interaction is greater when linguistic stimuli are presented to the right hemisphere instead of the language-dominant left hemisphere.

Furthermore, the results indicated faster reaction times and less identification errors for the bilingual participants compared to the monolingual participants regardless of stuttering. BWNS have been found to have an advantage in executive functioning over MWNS (Bak et al., 2014; Sullivan et al., 2014). This bilingual advantage has been found for attentional tasks that require task switching and inhibitory control (Calvo & Bialystok, 2014; Kroll & Bialystok, 2013; Soveri, Laine, et al., 2011). However, there are reports of differences in the bilingual advantage between simultaneous and sequential BWNS (Bak et al., 2014; Tao, Marzecova, Taft, Asanowicz, & Wodniecka, 2011). Both Bak et al. (2014) and Tao et al. (2011) discovered that simultaneous BWNS mainly benefited from task switching and sequential BWNS mainly benefited from inhibitory control. The results from the current study appear to be consistent with this view. Participants were required to attend only to one visual field, while ignoring the stimulus in the other visual field. The sequential BWNS demonstrated faster reaction times than the MWNS for both the LVF and RVF. Therefore, the bilingual advantage for selective attention suggested by Bak et al. (2014) was evident for the sequential BWNS from the present study. Interestingly, this advantage was also found for the BWS group, and no differences in reaction times or error rates compared to BWNS were observed. In contrast, the MWS group demonstrated slower reaction times and more errors for both the LVF and RVF compared to the BWS group. Furthermore, the MWS also showed more errors than the MWNS group for the RVF. Past researchers have found deficits in MWS in a number of executive function domains, resulting in slower reaction times and higher error rates in word recall accuracy and recognition (Byrd, Sheng, Bernstein Ratner, & Gkalitsiou, 2015; Eggers et al., 2013; Heitmann et al., 2004; Liu et al., 2014; Maxfield et al., 2015). A similar effect was revealed for the MWS compared to the MWNS, as well as the BWS, in the present study. Therefore, it appears that bilingualism is able to offset some of the deficits in executive functioning that have been attributed to stuttering. Hence, the results of the present study lend support to previous findings implicating the benefits of bilingualism.

Declaration of interest

The authors report no conflicts of interest.

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