TITLE: Bilingual language experience and the neural underpinnings of working memory.

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Abstract

A longstanding question in cognitive neuroscience and in the bilingualism literature is how early language experience influences brain development and cognitive outcomes, and whether these effects are global or specific to language-related processes. The current investigation examined the effect of the timing of language learning on the performance and neural correlates of phonological and non-verbal working memory, subcomponents of executive function. Three groups of bilinguals, who varied in terms of the timing of second language learning (i.e., simultaneous bilinguals learned their two languages from birth; early and late bilinguals who learned their second language before or after 5 years of age, respectively), performed phonological and non-verbal working memory tasks in the magnetic resonance imaging scanner. Results showed that there were no group differences in performance on either of the tasks, or in the neural correlates of performance of the non-verbal task. However, critically, we showed that despite similar behavioural performance, the groups differed in the patterns of neural recruitment during performance of the phonological working memory task. The pattern of group differences was non-linear, demonstrating similar neural recruitment for simultaneous and late bilinguals that differed from early bilinguals. Findings from the current study suggest a dynamic mapping between the brain and cognition, contributing to our current understanding of the effect of the timing of language learning on cognitive processes and demonstrating a specific effect on language-related executive function.

Keywords: bilingualism; working memory; phonological working memory; non-verbal working memory; functional magnetic resonance imaging (fMRI); age of acquisition

1. INTRODUCTION

An important question in cognitive neuroscience is how early language experience influences brain development, and whether these experiences affect all aspects of brain development and cognition in the same way, or whether there are differential effects across different brain regions and cognitive processes. Given that most individuals are exposed to a native language from birth and many individuals learn a second language in the first years of life, language experience is a unique experiential variable that allows for experimental investigations in terms of experience with learning a second language, providing important insights about the effects of very early experience on brain plasticity. For example, the timing of learning a second language can coincide with the learning of a native language (i.e., from birth) or it can occur at a later point during development (e.g., school age). It is known that the developing brain is more sensitive than the developed brain, and that the same experience occurring at different points in development can result in qualitatively different effects on the brain (e.g., Kolb & Gibb, 2011). The question that arises is whether exposure to a second language very early in life, during a period of enhanced neuroplasticity, will affect all cognitive outcomes later in life or be specific to the language domain, and whether this may differ as a function of when a second language has been learned due to changes in neuroplasticity that occur during development.

One important factor that sets this study apart from previous studies is that we explore the neural underpinnings of WM in a group of bilinguals who differed with respect to their non-native language experience, whereas the majority of previous (mostly) behavioural work has compared monolinguals to bilinguals, with a single bilingual group being largely variable in terms of language experience. Previous research has suggested that the impact of bilingualism on cognitive control (including WM) may differ as a function of the linguistic demands of the task (e.g., Hansen et al., 2016; Kousaie & Phillips, 2017; Luo et al., 2013). For example, with respect to WM specifically, Luo et al (2013) found that across the adult lifespan, bilinguals outperformed monolinguals on a spatial WM task, whereas monolinguals outperformed bilinguals on a verbal WM task. Furthermore, Hansen et al. (2016) showed that bilingualism modulates the trajectory of development of non-linguistic executive function and linguistic processing abilities, with bilingual children showing superior executive function and poorer linguistic processing compared to monolingual children at earlier stages of second language immersion. In the current study we compared the effects of language experience on phonological and non-verbal WM in the same group of young bilingual adult participants. Rather than comparing monolinguals and bilinguals, the variability within a single group of bilinguals and how this may influence both behavioural performance and the neural underpinnings of phonological and non-verbal WM is the question of interest in the current study. Given the differential involvement of language processes in phonological and non-verbal working memory, identifying the influence of language experience on these different aspects of WM furthers our understanding of the nature of the effects of language experience on brain development and cognitive outcomes. Specifically, this study provides information about whether the effects of language experience on cognitive processes, WM in particular, are specific to cognitive processes involving language or whether they generalize to other processes, for instance non-verbal processes. The current investigation aimed to shed light on how early language experiences may interact with the development of working memory (WM) and in what way this might exert an influence on the neural substrates supporting phonological language processes as compared to non-verbal WM.

WM is a component of executive function comprised of a limited capacity cognitive system that is responsible for the temporary storage and manipulation of information (Baddeley & Hitch, 1974), with the phonological and visuospatial components of WM having different roles. While phonological WM stores and manipulates incoming phonological information (Baddeley et al., 1998) and is important for facilitating the acquisition and processing of vocabulary and grammar in a language (e.g., Gathercole, 2006; Gathercole et al., 1992; Silbert et al., 2015), visuospatial/non-verbal WM is responsible for the temporary maintenance of visual/non-verbal information necessary for the performance of other tasks (Luck & Vogel, 2013), such as information about faces, shapes and images. These two subcomponents of WM have been further differentiated based on the brain regions recruited during task performance. Specifically, WM is generally subserved by a bilateral frontoparietal network of brain regions (Ray et al., 2008; Rottschy et al., 2012); however, verbal WM tasks show greater recruitment of the left inferior frontal gyrus compared to non-verbal WM tasks (see meta-analysis by Rottschy et al., 2012), and of left frontal and temporal lobes compared to spatial WM tasks (Ray et al., 2008). On the other hand, the left (pre) supplementary motor area and bilateral dorsal premotor cortex have been associated with non-verbal WM task performance (see meta-analysis by Rottschy et al., 2012). Thus, given that phonological and non-verbal WM have dissociable neural correlates, and that the brain regions associated with phonological WM overlap with some classic language regions (e.g., left inferior frontal gyrus; Price, 2000), it is possible that language experience may differentially impact the development of these two subcomponents of WM.

In terms of bilingual language processing, in a recent meta-analysis, Cargnelutti et al. (2019) showed that the timing of language learning was associated with different patterns of brain activation for a native language (L1) and a second language (L2) in general. Additionally, greater recruitment of bilateral frontal regions including the left inferior and superior frontal gyri, left precentral gyrus, and right middle frontal gyrus, as well as the left superior parietal gyrus and the cerebellum has been found during phonological processing in an L2 compared to an L1 (Sulpizio et al., 2020). Brain regions showing greater recruitment for phonological processing in the L1 compared to the L2 were limited to the left inferior frontal gyrus and the right middle temporal gyrus (Sulpizio et al., 2020). However, little research to date has investigated the impact of bilingual language experience specifically on the phonological and non-verbal subcomponents of WM. Taken together, one might expect that early language experience would have dissociable effects on the neural underpinnings of these two subcomponents of WM based on previous research demonstrating differences in the neural substrates of phonological and non-verbal WM (Ray et al., 2008; Rottschy et al., 2012), and the overlap between regions implicated in phonological WM and bilingual phonological processing more generally (e.g., inferior frontal and temporal cortices).

The majority of previous research examining WM and bilingualism is based on behavioural studies. While some studies have found that bilinguals outperform monolinguals (e.g., Antón et al., 2019; Morales et al., 2013), others find domain-specific effects with bilinguals outperforming monolinguals only on spatial WM tasks and an opposite pattern for verbal WM tasks (Luo et al., 2013). One study that compared monolingual children to age-matched second language learners at different grade levels found that bilingualism interacted with the components of WM such that monolinguals outperformed bilinguals on a verbal WM task at earlier grades, while the opposite was observed for a non-verbal WM task (Hansen et al., 2016). One recent study compared phonological short-term and visuospatial memory performance across monolinguals, bilinguals who learned their two languages simultaneously from birth (i.e., simultaneous bilinguals), L2 learners who learned their L2 at a mean age of 15 years old, and multilinguals who learned two languages simultaneously and at least one other language after puberty (Durand López, 2021). The results of this study found that multilinguals and L2 learners demonstrate superior phonological short-term memory compared to simultaneous bilinguals, who have two native languages, whereas multilinguals and L2 learners with intermediate proficiency showed superior visuospatial memory compared to monolinguals. These recent findings suggest that both the timing of L2 learning and attained proficiency in an L2 have an impact on behavioural WM performance, and these effects differ depending on the subcomponent of WM investigated. The current investigation uses functional magnetic resonance imaging (fMRI) to directly compare the neural correlates of performance during phonological and non-verbal WM task performance and relates this to the timing of L2 learning in bilinguals.

The neural underpinnings of phonological WM as it relates to language acquisition is of relevance to questions about bilingual language processing and cognition; however, studies examining the interaction between phonological working memory and bilingual language experience using measures of brain function are limited in the literature. In one study, Pierce et al. (2015) found that early exposure to a language influences phonological WM processes, even when the language of initial exposure is discontinued. In their study, international adoptees who had discontinued use of their first exposed language before the age of 3 years and who were functionally monolingual in their second language showed similar neural recruitment as bilinguals during the performance of a phonological WM task. Furthermore, compared to monolinguals, both the bilinguals and international adoptees showed greater recruitment of brain regions involved in cognitive control during task performance, raising questions about the impact of language experience on the development of phonological WM within bilingual individuals, and how this may generalize to other non-language-related cognitive processes. This has been addressed to some extent in the literature, with research suggesting that, in terms of behaviour, early second language learners demonstrate superior verbal WM performance compared to late learners (Vejnovic et al., 2010), and simultaneous bilinguals outperform both early and late bilinguals (Delcenserie & Genesee, 2017).

The current study builds on this earlier work, but adds to the literature by directly examining the link between bilingual language experience (i.e., the timing of L2 learning) and the neural underpinnings of phonological WM. Furthermore, we examined groups of bilinguals in order to shed light on the effect of language experience within bilingual individuals and compared phonological and non-verbal subcomponents of WM in order to examine the effect of language experience more globally. Using measures of behaviour and neuroimaging, we show that language experience does not affect behavioural performance, nor does it impact cognition more globally, but is rather uniquely associated with the neural correlates of phonological WM. These findings are important, demonstrating that bilingual language experience is associated specifically with the subcomponent of WM that is involved in language processing. Furthermore, the influence of the timing of L2 learning on the neural correlates of phonological WM is not linear, yielding potential implications for the understanding of bilingual language acquisition and for bilingual educational policy.

2. MATERIALS AND METHODS

2.1 Participants

Thirty-one right-handed bilingual young adults proficient in English and French participated in this study. Participants were divided into three groups based on the timing of second language learning: simultaneous bilinguals (n=10) who had learned both of their languages from birth; early bilinguals (n=11) who learned their second language at an average of 4.7 years old (*SD*=0.6); and late bilinguals (n=10) who learned their second language at an average of 7.9 years old (*SD*=2.1); sample size in each group was based on the availability of participants who met the inclusion criteria with the goal of a minimum of 10 participants per group, in line with a previous study that used similar methodology (Pierce et al., 2015). The groups were matched in terms of chronological age, formal education, language fluency, and general intelligence. Demographic information is provided in Table 1. At the time of testing, participants were fluent in both English and French and did not have knowledge of any other languages, they had pure-tone hearing thresholds within the normal range, no history of any medical conditions or medications known to affect cognitive functioning and did not have any conditions incompatible with MRI (e.g., metal implants, claustrophobia). All participants were non-musicians to control for any effects that musical training may have on brain organization (e.g., Gaser & Schlaug, 2003). At the time of the study, participants were living in a highly bilingual city, Montreal, with regular exposure to both English and French in their daily lives. Based on self-report daily usage measures, on average participants used their L1 66% of the time and their L2 34% of the time. Pairwise t-tests showed no difference in the proportion of daily usage of each language across the three groups of participants.

Table 1. *Demographic information (mean (SD)) for the three participant groups.*

	Simultaneous (n=10; 4 males[*])	Early (n=11; 2 males*)	Late (n=10; 4 males*)	*p* (one-way ANOVA)
Age	22.8 *(2.3)*	24.1 *(4.0)*	24.8 *(3.6)*	.41
Education	15.7 *(1.6)*	15.4 *(1.7)*	15.0 *(2.1)*	.69
AoA[a]	0 *(0)*	4.7 *(0.6)*	7.9 *(2.1)*	**<.001**
Matrix reasoning[b]	12.0 *(2.6)*	11.5 *(2.4)*	12.2 *(3.0)*	.81
L1 letter fluency	40.6 *(14.6)*	41.7 *(9.3)*	37.9 *(14.1)*	.79
L1 category fluency	23.0 *(6.1)*	21.1 *(7.0)*	24.0 *(8.3)*	.64
L2 letter fluency	34 *(9.1)*	27.3 *(10.5)*	24.8 *(10.6)*	.13
L2 category fluency	16.8 *(3.7)*	14.8 (*4.0)*	13.9 *(4.6)*	.29

[*] Given the difference in gender distribution across the groups, supplemental analyses were carried out to ensure that gender was not driving our results

[a] Age of second language acquisition

[b] Matrix reasoning subtest of the Wechsler Adult Intelligence scale IV (Wechsler, 2008); scaled score maximum 19

2.2 Stimuli and Materials

2.2.1 Assessment of language proficiency. In addition to self-reporting their proficiency in French and English, objective language proficiency in the two languages was measured using letter and category fluency tasks in each language; scores are reported in Table 1.

In the letter fluency tasks, participants produced as many words as they could think of in one minute that started with a specific letter of the alphabet. Proper nouns, numbers, or words differing from an accepted word only in terms of suffix (e.g., love, lover, loving) were excluded. Three letters in each language (*F*, *A*, and *S* in English; *P*, *F*, and *L* in French) were included and each participant's score reflects the total number of words produced in each language.

The category fluency task was similar to the letter fluency tasks; however, participants were required to produce as many exemplars as possible from a specific category in one minute (*animals* in English; *fruits* in French). Each participant's score reflects the total number of correct exemplars produced per language.

2.2.2 Assessment of general intelligence. The Matrix Reasoning subtest of the Wechsler Adult Intelligence Scale Fourth Edition (WAIS-IV; Wechsler, 2008) was used as a proxy to assess general intelligence; standardized scores are reported in Table 1. For this task, participants were presented with a series of 26 designs increasing in complexity and were required to identify patterns in each design by selecting from five alternatives the item that completed the pattern.

2.2.3 Phonological working memory task. To test phonological WM, a phonological n-back task including three blocked conditions that increased in terms of WM demands was used. In the 0-back condition, the target stimulus was identified at the beginning of the block and the participant was required to press a button each time they heard the target. In the 1-back and 2-back conditions, the participant was required to press a button to identify whether the current stimulus matched the stimulus that immediately preceded it (1-back condition) or the stimulus that was presented 2 previous (2-back condition). Within each block, the conditions were separated by a baseline condition that consisted of five trials during which participants fixated on a "+" presented in the center of the screen. The stimuli included pseudowords in French and

English. Stimuli in the French version of the task were 36-bisyllabic pseudowords that differed from real French words by one phoneme. These stimuli have previously been used to examine phonological WM in bilinguals (Chee et al., 2004; Pierce et al., 2015) and a similar protocol was used in the current study. An equivalent English version of the task was created by creating a list of French real words based on the French pseudoword stimuli. Spoken word frequency for the list of French words was obtained (New, 2006) and a list of English words, matched for spoken word frequency (Kerkman et al., 1993) was created. English pseudowords were created by changing a single phoneme in the real word and ensuring that the resulting list of English and French pseudowords were matched for phonological neighborhood density (Marian et al., 2012).

Stimuli were recorded by a bilingual female speaker who had learned English and French simultaneously from birth and who was equally proficient in the two languages with no detectable accent in either language. Two experimental runs lasting 6:20 minutes were completed in each language (4 runs total) in the MRI scanner. Each run consisted of two blocks each of the 0-back, 1-back, and 2-back conditions, with each condition comprised of 4 target and 8 non-target auditory stimuli (i.e., a total of 12 auditory stimuli in each condition).

Stimuli were presented to participants binaurally through MRI compatible Sensimetrics S14 insert earphones (Sensimetrics Corporation) with Comply Foam canal tips (Hearing Components, Oakdale MN) using E-prime 2.0 (SP1) presentation software (Psychology Software Tools, Pittsburgh, PA). On average, recordings were 669 ms in length and stimulus presentation lasted 1000 ms, with image acquisition occurring after the presentation of the auditory stimulus. This timing was necessary to ensure that auditory stimuli were presented in quiet. Sparse sampling in the MRI scanner was employed with auditory stimuli presented between image acquisitions. In total, each trial lasted 3260 ms, which included stimulus presentation (1000 ms) and image acquisition (2260 ms).

2.2.4 Non-verbal working memory task. In order to measure non-verbal WM, we used a task designed and validated by Petrides and colleagues (e.g., see Chen et al., 2004). The task included a WM condition and a baseline condition. In the WM condition, participants were familiarized with five abstract images. During each trial, four of the five images were presented, one at a time, in random order at the center of the computer screen and participants were required to monitor the occurrence of the images. Following presentation of the fourth item, there was a 1 second delay, after which a test item was presented, and the participant was required to indicate if the test item was one of the four items presented during the trial ("yes" response) or whether it was the fifth item from the set ("no" response). Participants had a maximum of 1.5 seconds to respond with a button press (yes = right button, no = left button) before the subsequent trial began. The WM and baseline conditions were identical, except for the stimuli. In the baseline control condition, participants were presented with abstract images that were unrelated to those in the WM condition. Participants were presented with four identical images followed by a test item. The test item was one of two images that the participants had learned to associate with a left or right response key prior to scanning. The non-verbal WM task was completed in the MRI scanner in two runs lasting 6:12 minutes each. Stimuli were presented using E-prime 2.0 (SP1) presentation software (Psychology Software Tools, Pittsburgh, PA) and images were acquired continuously.

2.3 Experimental and Scanning Procedure

Participants completed the study over two testing sessions within 15 days of each other. A behavioural session lasting approximately 90 minutes was completed as well as a scanning session that lasted approximately 2.5 hours. During the behavioural testing session participants completed the Language and Health History Questionnaire, the letter and category fluency tasks, and the Matrix Reasoning subtest of the WAIS-IV (Wechsler, 2008). During the scanning session, an anatomical scan was acquired, and participants completed the two functional MRI tasks included in the current investigation, as well as a speech perception in noise task, and a resting-state functional MRI scan (data from these additional acquisitions have previously been published; see Kousaie et al., 2019; Kousaie et al., 2017). Participants were familiarized with the functional MRI tasks prior to entering the scanner. This study was approved by the Research Ethics Board at the Montreal Neurological Institute, McGill University, and participants gave their written consent prior to participations.

Imaging was performed at the McConnell Brain Imaging Centre at the Montreal Neurological Institute on a 3T TrioTim Siemens scanner using a 32-channel head coil. Functional images for the non-verbal task were acquired with a T_2*-weighted gradient echo-planar imaging sequence (EPI) in 37 4.0mm thick transverse slices covering the entire brain (TR=3000 ms, TE=30 ms, FoV=300 mm, flip angle=90 degrees, interleaved excitation); a total of 122 volumes were obtained in each run. Functional images for the phonological task were acquired with a T_2*-weighted gradient echo-planar imaging sequence (EPI) in 38 3.5mm thick transverse slices covering the entire brain (TR=3260 ms, TE=30 ms, FoV=224 mm, flip angle=90 degrees, interleaved excitation); a total of 115 volumes were obtained in each run. High-resolution T_1-weighted images were obtained from a 3D magnetization prepared rapid acquisition gradient echo (MP-RAGE) sequence (slice thickness=1 mm, TR=2300 ms, TE=2.98 ms, matrix size=256 x 256, FoV=256 mm, flip angle=9°, interleaved excitation) for each participant and used as an anatomical reference. For both functional tasks, visual stimuli were presented to participants via a mirror mounted on the head coil that reflected the information projected onto a screen placed at the back of the scanner.

3. ANALYSIS AND RESULTS

3.1 Behavioural results

Accuracy and response time data from each task were analyzed with separate analyses of variance (ANOVA) using SPSS v.24. Two Language Group (simultaneous vs. early vs. late) x Condition ANOVAs were conducted on the non-verbal WM task (one for each behavioural measure) and two Language Group (simultaneous vs. early vs. late) x Language (L1 vs. L2) x Condition (0-back vs. 1-back vs. 2-back) ANOVAs were conducted for the phonological WM task (one for each behavioural measure). One participant from the simultaneous group did not have any behavioural data due to a technical error and a second participant, from the early group, was excluded from the analysis of the phonological n-back response time data due to having 0 correct responses on one task condition.

Analysis of both the accuracy and response time data from the non-verbal WM task revealed a main effect of Condition (accuracy: $F(1,27)=44.2$, $MSE=1.2$, $n_p^2=.62$, $p<.001$; response time: $F(1,27)=63.3$, $MSE=7250.5$, $n_p^2=.86$, $p<.001$), demonstrating more accurate and faster responses for the baseline compared to the working memory condition.

Analysis of the phonological WM accuracy data revealed a main effect of Condition $F(2,54)=10.2$, $MSE=0.02$, $n_p^2=.26$, $p<.001$, with more accurate responses for the 0-back ($M=78\%$, $SE=.04$) and 1-back conditions ($M=82\%$, $SE=.03$), which did not differ, compared to the 2-back condition ($M=70\%$, $SE=.05$). There was also a Language x Condition interaction, $F(2,54)=3.5$, $MSE=0.05$, $n_p^2=.12$ $p=.04$, demonstrating a similar effect of Condition in both languages, but the difference in accuracy between the 0-back and 2-back conditions in the L2 was not statistically significant (p=.09). In terms of the response time data, there was again a main effect of Condition, $F(2,52)=10.0$, $MSE=376.6$, $n_p^2=.28$, $p<.001$, demonstrating faster responses for the 1-back condition (M=692.5 ms, SE=18.1) compared to the 0-back (M=731.1 ms, SE=20.1) and 2-back (M=717.0 ms, SE=20.8) conditions, which did not differ.

The effects of Condition observed for both tasks demonstrate the expected WM effects. Critically, there were no significant effects of Language Group in any of the behavioural analyses (all p's > .33), demonstrating that participants showed similar behavioural performance on both measures of WM irrespective of when they learned their second language. Figure 1 displays the significant effects observed in the behavioural data.

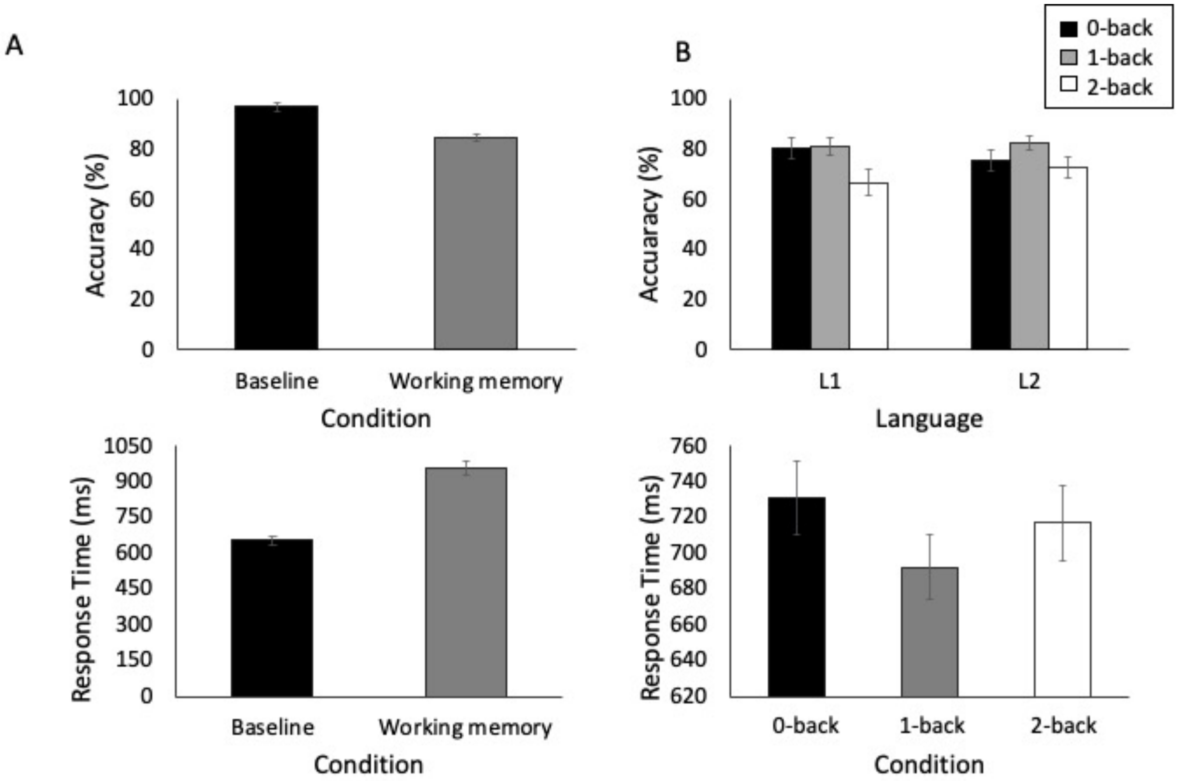

Figure 1. Behavioural data for the non-verbal (panel A) and phonological (panel B) WM tasks. Panels A (top and bottom) and B (bottom) show the main effect of Condition observed in non-verbal WM accuracy and response time, and phonological WM response time, respectively;

panel B (top) shows the Language x Condition interaction observed in accuracy on the phonological WM task.

3.2 Task-based functional MRI

The functional imaging data were preprocessed and analyzed using SPM12 (Wellcome Department of Imaging Neuroscience, London, UK). Preprocessing followed standard steps, including slice time correction, realignment and unwarping, segmentation, normalization in MNI space and smoothing with a 6 mm full width at half maximum (FWHM) Gaussian kernel. Artifact and outlier scans were identified, using ART (Artifact Detection Tools; https://www.nitrc.org/projects/artifact_detect/), as images in which the average intensity deviated more that 3 standard deviations from the mean intensity in the session, or composite head movement exceeded 1.5 mm from the previous image. A total of 6% and 2.8% of trials were identified as artifacts/outliers and were removed from subsequent analyses for the phonological and non-verbal tasks, respectively. First level contrasts comparing each of the experimental conditions (i.e., 0-back, 1-back, 2-back in each language compared to baseline for the phonological WM task and working memory-baseline for the non-verbal WM task) were created for each participant and further analyzed at the second level. We first report the direct comparison of the phonological and non-verbal tasks to identify the brain regions recruited consistently across the two tasks and those unique to each task, demonstrating consistency with the previous literature. This is followed by an analysis of the effect of Language Group for each task separately, which is the crucial analysis necessary to address our research question.

3.2.1 Direct comparison of phonological and non-verbal WM tasks. First, we directly compared the two tasks across all participants to identify common and independent regions that are implicated in task performance; all reported results were significant at p(uncorrected)<.001, k>150 and survived cluster-wise p(FDR)<.05. To isolate WM in the phonological WM task we created first-level contrasts comparing 2-back and 0-back conditions. Given that there were no significant effects of Language (see results from the Language Group x Language x Condition ANOVA reported below) we collapsed across language in this analysis to increase power. A whole-brain conjunction analysis revealed that the bilateral IPL, left precentral gyrus, left supplementary motor area and right middle frontal gyrus were recruited during both phonological and non-verbal WM performance (see Figure 2). A whole-brain paired samples t-test was used to determine the brain regions that were implicated in each task independently. There was greater recruitment of the bilateral IPL, left superior frontal gyrus, right supplementary motor area and right inferior frontal gyrus for phonological WM compared to non-verbal WM, whereas bilateral occipital cortex was recruited more for non-verbal WM than for phonological WM. See Table 2 for peak coordinates.

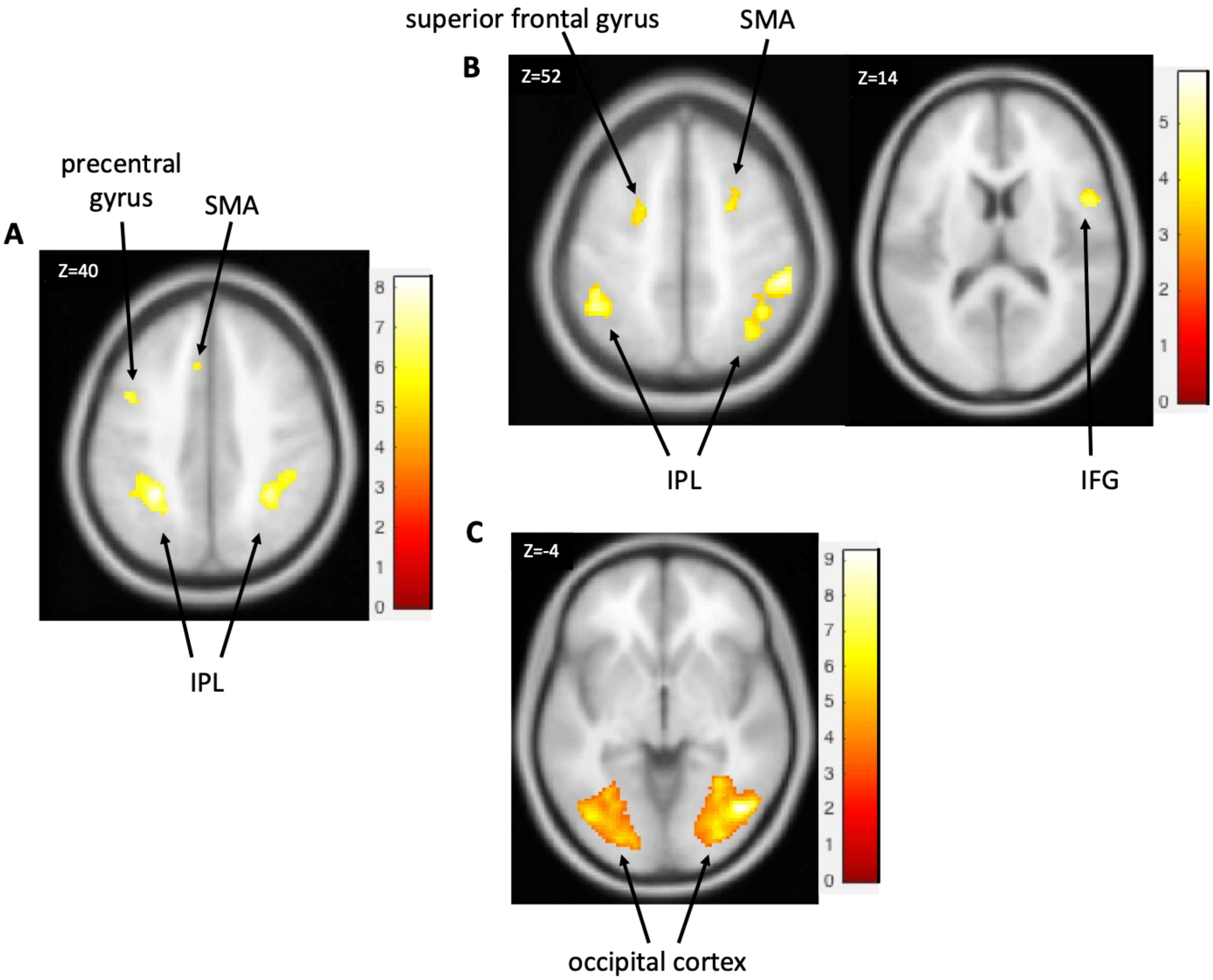

Figure 2. T-maps showing brain regions that were recruited for both tasks (conjunction analysis; Panel A) and regions that were recruited to a greater extent during phonological compared to non-verbal WM performance (Panel B) and during non-verbal compared to phonological WM performance (Panel C). (IPL=inferior parietal lobule; SMA=supplementary motor area; IFG=inferior frontal gyrus)

Table 2. *Results of the comparison of phonological and non-verbal working memory. Peak voxels, cluster extent and z-score are shown for each main effect. Results of the comparisons between the tasks were obtained with a whole-brain p(uncorrected)<.001 and k>150, and survived p(FDR)<.05.*

Brain region	Cluster extent (voxels)	Peak MNI coordinates (x,y,z mm)	z-score
Conjunction analysis			
Left IPL	473	-30 -48 40	6.72
Left precentral gyrus	212	-44 6 38	6.12
Left SMA	153	-6 10 52	5.84
Right IPL	598	32 - 50 42	6.19
Right middle frontal gyrus	82	32 -4 60	5.36
Phonological > Non-verbal			
Left IPL	606	-44 -48 50	4.61
Left superior frontal	167	-24 2 62	4.57
Right IPL	646	50 -36 50	4.78
Right SMA	220	28 0 62	4.70
Right IFG	156	52 10 18	4.33
Non-verbal > Phonological			
Left occipital cortex	4097	42 -68 -4	6.31
Right occipital cortex	3818	-24 -84 18	5.74

Note: IPL=inferior parietal lobule; SMA=supplementary motor area; IFG=inferior frontal gyrus

3.2.2 Group differences in neural recruitment during WM performance. To examine the effect of language experience on neural recruitment during non-verbal WM performance, we conducted a whole-brain one-way ANOVA comparing the groups on the working memory vs. baseline first-level contrast from the non-verbal task. Average neural activity across the groups showed greater activity for the WM condition in a network of regions consistent with those typically involved in working memory (e.g., Eriksson et al., 2015), including bilateral frontal, inferior parietal and occipital regions (whole-brain p(FWE)<.05; k>50). Critically, there was no effect of Language Group in this analysis.

Given the multiple conditions in the phonological WM task, we ran a whole-brain Language Group (simultaneous vs. early vs. late) x Language (L1 vs. L2) x Condition (0-back vs. 1-back vs. 2-back) ANOVA on the fMRI data to identify whether the timing of second language learning was associated with the neural basis of phonological WM, and whether this differed as a function of language. This analysis showed three brain regions where neural recruitment was differentiated by group membership. Specifically, a main effect of Language Group was found in the left superior temporal gyrus (STG), the left anterior insula and the right dorsolateral prefrontal and anterior cingulate cortex (DLPFC/ACC). We also found a main effect of Condition in bilateral inferior parietal lobule (IPL) and middle frontal gyrus (MFG) (whole-brain p(FWE)<.05; k>70). See Table 3 for peak coordinates. There were no other significant effects or interactions.

Table 3. *Results of Language Group x Language x Condition ANOVA. Peak voxels, cluster extent and z-score are shown for each main effect. All results were obtained with a whole-brain p(FWE)<.05 and k>70.*

Brain region	Cluster extent (voxels)	Peak MNI coordinates (x,y,z mm)	z-score
Main effect of Language Group			
Left STG	119	-54 -12 10	7.23
Left anterior insula	73	-30 28 18	6.16
Right DLPFC/ACC	120	30 44 34	6.41
Main effect of Condition			
Left IPL	354	-32 -48 40	6.36
Left MFG	77	-24 -2 50	6.15
Right IPL	389	40 -38 38	6.32
Right MFG	130	26 2 52	5.86

Note: STG=superior temporal gyrus; DLPFC/ACC= dorsolateral prefrontal and anterior cingulate cortex; IPL=inferior parietal lobule; MFG=middle frontal gyrus

To determine the source of the observed main effect of Language Group, we extracted the blood-oxygen-level dependent (BOLD) activity from each of the three clusters using the *rex* tool in MATLAB and subsequently analyzed these data with a one-way ANOVA in SPSS v.24 for each cluster. These analyses showed that the main effect resulted from greater neural recruitment in the simultaneous and late bilinguals compared to the early group. This was true for all three brain regions: left STG: $F(2,28)=17.0$, $MSE=15.2$, $n_p^2=.55$, $p<.001$; left insula:

$F(2,28)=9.6$, $MSE=3.6$, $n_p^2=.41$, $p=.001$; and right DLPFC/ACC: $F(2,28)=9.7$, $MSE=16.5$, $n_p^2=.41$, $p=.001$; see Figure 3.

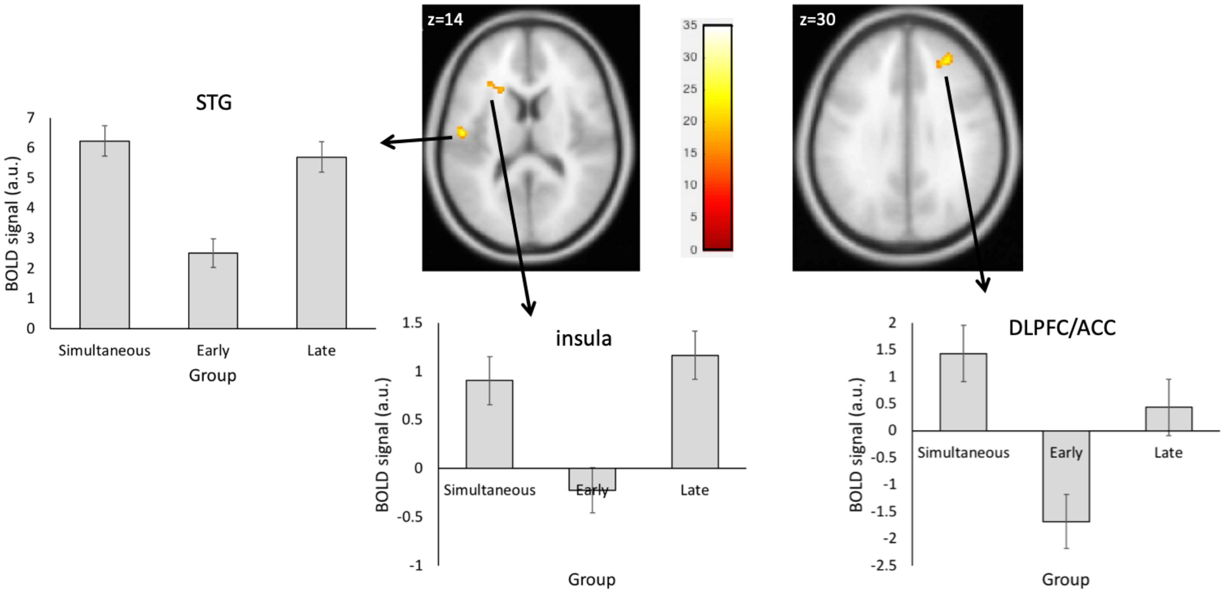

Figure 3. F-maps showing the brain regions in which there was a main effect of Language Group on neural recruitment during phonological WM task performance and the average BOLD signal in each region as a function of Language Group. (STG=superior temporal gyrus; DLPFC/ACC=dorsolateral prefrontal and anterior cingulate cortex)

4. DISCUSSION

We examined the impact of early language experience on the neural underpinnings of the phonological and non-verbal WM components of executive function. Given the involvement of phonological WM in language development and learning, we were particularly interested in how the age of L2 learning may impact this aspect of WM and whether the effect of age of L2 acquisition would differ across the phonological and non-verbal WM tasks.

Overall, the behavioural data show the expected condition effects in both tasks, demonstrating decreasing performance with increasing WM demands. These results indicate that the tasks effectively measured WM in our participants. Critically, we observed no differences in behaviour between our groups for either the phonological or non-verbal WM tasks. Thus, the findings suggest that there is no effect of the timing of language learning on behavioural WM performance for either phonological or non-verbal WM in our group of bilinguals. This is in contrast to previous studies that have observed differences between monolinguals and bilinguals (Antón et al., 2019; Hansen et al., 2016; Luo et al., 2013; Morales et al., 2013), as well as between simultaneous and later learners of an L2 (Durand López, 2021). This inconsistency may be the result of differences in the timing of L2 learning between the samples used in the different studies, with groups in the current study having more subtle differences in the timing of L2 learning across groups compared to studies comparing groups that differ more substantially in terms of timing of L2 language learning. It is noteworthy that our results are consistent with a previous study that used the same French task used here (Pierce et al., 2015). Importantly, we show that despite the similar behavioural performance, our language groups relied on different neural substrates during phonological WM task performance. This finding suggests that the timing of L2 learning influences how the brain processes phonological information, at least in the context of our phonological WM task, even when this is not evident in overt behaviour, which has implications for language learning as it may indicate optimal time points for learning or optimal learning strategies depending on the timing of learning.

The main effect of Language Group from the analysis of the phonological WM task showed that the timing of language learning was associated with differential recruitment of left STG and anterior insula, as well as the right DLPFC/ACC. The implicated regions are not surprising given the role of the insula and the DLPFC/ACC in executive control and the role of the left STG in the processing of language relevant auditory information. However, the pattern of this effect shows that the simultaneous and late bilinguals recruited these regions more than the early bilinguals, which implies that the relation between the age of L2 learning and phonological WM is not linear. Previous research suggests dynamic effects of learning an L2 on brain structure, with initial increases in L2 language experience being associated with increases in cortical grey matter volume in a network of temporo-parietal regions and regions implicated in executive control (e.g., inferior and middle frontal gyrus, ACC) followed by additional changes in these structural adaptations with additional language experience (e.g., return to baseline volume), with possible variability in these additional cortical changes depending on language exposure/usage factors (Pliatsikas, 2020). Thus, our findings are not the first to suggest that the effect of language experience on the brain is more complex than a simple linear relation between experience and brain function (or structure).

While the Dynamic Restructuring Model describes structural changes in the brain in relation to bilingual language experience (Pliatsikas, 2020), the current study focusses specifically on brain function during phonological working memory task performance. One theory that may help explain our results is the Interactive Specialization framework, which proposes that the mapping between the brain and cognition is dynamic and changing, and that the same behaviour may have different neural underpinnings at different ages during development (Johnson, 2011). Based on this framework, our results suggest that learning a second language at different points in development may rely on different neural substrates, at least in relation to phonological WM. Indeed, early work on phonological memory and vocabulary development has suggested that the interaction between these two constructs changes over the course of development (Gathercole et al., 1992), thus it follows that perhaps the neural substrates underlying these processes also change with development. Specifically, until the age of 5, phonological WM has an influence on vocabulary acquisition, whereas after age 5 this relationship is reversed. Given that age 5 was the cutoff between our early and late bilingual groups, the shift in importance of phonological WM for vocabulary development in combination with the Interactive Specialization theory may explain the results from the current investigation. That is, the shift in the relationship between phonological WM that occurs at age 5 may be associated with a shift in the neural substrates underlying these processes, thus the effects of learning an L2 before 5 years old vs. after 5 years old could rely on and recruit different brain regions, such as those observed in the current study (i.e., left STG and anterior insula, and right DLPFC/ACC).

However, if the shift in the importance of phonological WM for vocabulary learning at age 5 is the critical determinant of the neural substrates for these processes, then one would expect that the simultaneous and early bilinguals would show a similar pattern of neural recruitment that is different from the late bilinguals. A possible explanation for our unpredicted finding (i.e., the late bilinguals show similar patterns of neural recruitment as the simultaneous bilinguals, which differs from the early bilinguals) is that the simultaneous bilinguals, who learned both of their languages at the same time from birth, are like monolinguals in that they have two first languages, an interpretation that is consistent with previous structural work (Klein et al., 2014). The early bilinguals in our study, on the other hand, started learning their L2 after their L1, but were still mastering their L1 at the same time, while the later bilinguals didn't start learning their L2 until their L1 was relatively well established. Thus, the late bilinguals may be recruiting the same regions at the simultaneous bilinguals because both of these groups are functionally like monolinguals; the simultaneous bilinguals are like monolinguals by having two native languages and the late bilinguals are like monolinguals because their L2 is mediated through their L1 as a result of having only learned their L2 after mastering their L1. Future research that includes a monolingual group could address this question more directly.

One limitation of our results is related to the type of L2 learning, for example formal learning in a school setting as compared to informal learning. Given that the age of L2 learning cut-off for inclusion in the early group was 5 years old, it is possible that there are differences between our groups in how they learned their L2, and this may have impacted our results. Most participants (27/31) provided information about when they started learning each of their languages at home and at school. In terms of formal learning, the only the simultaneous (*M*=4.4, *SD*=0.9) and late (*M*=7.4, *SD*=2.1) groups differed with respect to when they started learning their L2 at school. Given that the simultaneous and late groups did not differ in terms of neural recruitment during phonological WM task performance, it is unlikely that this is a potential confound that can account for our findings. We do not have specific information regarding the number of years of education that participants received in each language, therefore a more nuanced relation between type of learning and phonological WM may provide an alternative explanation for our results but remains a question for future research.

In terms of the more general fMRI results, we found that a similar network of fronto-parietal brain regions, consistent with previous research (Eriksson et al., 2015), was recruited for both non-verbal and phonological WM. We also observed task-specific regions of activation that were not unexpected given the task-demands associated with each task. Specifically, we found greater recruitment of regions associated with phonological processing for the phonological WM task and greater recruitment of visual cortex for the non-verbal task. However, the most important finding from this study was group differences in terms of neural recruitment during phonological WM task performance, but not during non-verbal WM task performance, suggesting a specific effect of the timing of language learning on phonological WM.

Given that previous research has primarily dichotomized the bilingual experience, our focus on different language experiences, specifically the timing of L2 learning, within bilinguals is a strength of the current study. The inclusion of a well-controlled bilingual sample resulted in a trade-off between controlling for confounding variables and sample size, resulting in our sample being relatively small. However, our sample included a total of 31 participants with at least 10 participants in each group and our results emerged from a whole brain analysis not restricted to a priori regions of interest, with significant findings surviving conservative statistical correction for multiple comparisons. Furthermore, although the study could benefit from increased power with a larger sample, the number of participants is comparable to that in published work using similar methodology (e.g., Chee et al., 2004; Pierce et al., 2015). We also included two specific tasks designed to dissociate between phonological and non-verbal WM to disentangle the effects of language experience on the subcomponents of WM. Future research should replicate the current study with a larger sample and the addition of a monolingual comparison group.

In conclusion, the current study explored the effects of early language experience on WM and demonstrated that despite the absence of behavioural differences, participants show a different pattern of neural activation specific to the phonological WM task, with no effect of the timing of L2 learning on non-verbal WM. Importantly, we show that the relationship between the timing of L2 learning and phonological WM is not linear and suggest that this is related to the dynamic mapping between the brain and cognition and a shift in the relevance of phonological WM for vocabulary learning that occurs around age 5. These findings contribute to our current understanding of the effects of the timing of language learning on cognitive processes and demonstrate the specific effect of the timing of L2 learning on a subcomponent of executive control that is involved in language processing. Our findings may have implications for bilingual language acquisition and education, for example, learning an L2 at a specific time during development may result in different outcomes in terms of brain organization for processing phonological information. Previously, we have shown that the timing of L2 learning is associated with superior cognitive control and more optimal intrinsic brain connectivity (Kousaie et al., 2017), thus the current study further demonstrates the impact of the timing of L2 learning on brain plasticity and is consistent with previous research (e.g., Pierce et al., 2015) demonstrating that early language experience has long-lasting effects on the brain and cognitive function. Our findings are relevant to second language educators and language policy. Specifically, our findings suggest that despite similarities in overt behaviour, differences in neural recruitment during phonological WM may point to differences in optimal learning strategies that can be applied based on age of learning and language background experience.

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References

Antón, E., Carreiras, M., & Duñabeitia, J. A. (2019). The impact of bilingualism on executive functions and working memory in young adults. *PLoS One*, *14*(2), e0206770. https://doi.org/10.1371/journal.pone.0206770

Baddeley, A. D., Gathercole, S., & Papagno, C. (1998). The phonological loop as a language learning device. *Psychological Review*, *105*(1), 158-173.

Baddeley, A. D., & Hitch, G. (1974). Working Memory. In G. H. Bower (Ed.), *Psychology of Learning and Motivation* (Vol. 8, pp. 47-89). Academic Press. https://doi.org/https://doi.org/10.1016/S0079-7421(08)60452-1

Cargnelutti, E., Tomasino, B., & Fabbro, F. (2019). Language brain representation in bilinguals with different age of appropriation and proficiency of the second language: A meta-analysis of functional imaging studies. *Frontiers in Human Neuroscience*, *13*, 154-154. https://doi.org/10.3389/fnhum.2019.00154

Chee, M. W., Soon, C. S., Lee, H. L., & Pallier, C. (2004). Left insula activation: a marker for language attainment in bilinguals. *Proceedings of the National Academy of Sciences of the United States of America*, *101*(42), 15265-15270. https://doi.org/10.1073/pnas.0403703101

Chen, J. K., Johnston, K. M., Frey, S., Petrides, M., Worsley, K., & Ptito, A. (2004). Functional abnormalities in symptomatic concussed athletes: an fMRI study. *NeuroImage*, *22*(1), 68-82. https://doi.org/http://dx.doi.org/10.1016/j.neuroimage.2003.12.032

Delcenserie, A., & Genesee, F. (2017). The effects of age of acquisition on verbal memory in bilinguals. *International Journal of Bilingualism*, *21*(5), 600-616. https://doi.org/10.1177/1367006916639158

Durand López, E. M. (2021). A bilingual advantage in memory capacity: Assessing the roles of proficiency, number of languages acquired and age of acquisition. *International Journal of Bilingualism*, *25*(3), 606-621. https://doi.org/10.1177/1367006920965714

Eriksson, J., Vogel, Edward K., Lansner, A., Bergström, F., & Nyberg, L. (2015). Neurocognitive architecture of working memory. *Neuron*, *88*(1), 33-46. https://doi.org/https://doi.org/10.1016/j.neuron.2015.09.020

Gaser, C., & Schlaug, G. (2003). Brain structures differ between musicians and non-musicians. *The Journal of Neuroscience*, *23*(27), 9240-9245.

Gathercole, S. E. (2006). Nonword repetition and word learning: The nature of the relationship. *Applied Psycholinguistics*, *27*(4), 513-543. https://doi.org/10.1017/S0142716406060383

Gathercole, S. E., Willis, C. S., Emslie, H., & Baddeley, A. D. (1992). Phonological memory and vocabulary development during the early school years: A longitudinal study. *Developmental Psychology*, *28*(5), 887-898. https://doi.org/10.1037/0012-1649.28.5.887

Hansen, L. B., Macizo, P., Duñabeitia, J. A., Saldaña, D., Carreiras, M., Fuentes, L. J., & Bajo, M. T. (2016). Emergent bilingualism and working memory development in school aged children. *Language Learning*, *66*(S2), 51-75. https://doi.org/10.1111/lang.12170

Johnson, M. H. (2011). Interactive Specialization: A domain-general framework for human functional brain development? *Developmental Cognitive Neuroscience*, *1*(1), 7-21. https://doi.org/https://doi.org/10.1016/j.dcn.2010.07.003

Kerkman, H., Piepenbrock, R., Baayen, R. H., Rijn, H. v., Burnage, G., & Linguistic Data, C. (1993). *The CELEX lexical database* Centre for Lexical Information, Max Planck Institute for Psycholinguistics.

Klein, D., Mok, K., Chen, J.-K., & Watkins, K. E. (2014). Age of language learning shapes brain structure: A cortical thickness study of bilingual and monolingual individuals. *Brain and Language*, *131*, 20-24. https://doi.org/http://dx.doi.org/10.1016/j.bandl.2013.05.014

Kolb, B., & Gibb, R. (2011). Brain plasticity and behaviour in the developing brain. *Journal of the Canadian Academy of Child and Adolescent Psychiatry = Journal de l'Academie canadienne de psychiatrie de l'enfant et de l'adolescent*, *20*(4), 265-276. https://pubmed.ncbi.nlm.nih.gov/22114608

https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3222570/

Kousaie, S., Baum, S., Phillips, N. A., Gracco, V., Titone, D., Chen, J. K., Chai, X. J., & Klein, D. (2019). Language learning experience and mastering the challenges of perceiving speech in noise. *Brain and Language*, *196*, 104645. https://doi.org/10.1016/j.bandl.2019.104645

Kousaie, S., Chai, X. J., Sander, K. M., & Klein, D. (2017). Simultaneous learning of two languages from birth positively impacts intrinsic functional connectivity and cognitive control. *Brain and Cognition*, *117*, 49-56. https://doi.org/http://dx.doi.org/10.1016/j.bandc.2017.06.003

Kousaie, S., & Phillips, N. A. (2017). A behavioural and electrophysiological investigation of the effect of bilingualism on aging and cognitive control. *Neuropsychologia*, *94*, 23-35. https://doi.org/10.1016/j.neuropsychologia.2016.11.013

Luck, S. J., & Vogel, E. K. (2013). Visual working memory capacity: from psychophysics and neurobiology to individual differences. *Trends in Cognitive Sciences*, *17*(8), 391-400. https://doi.org/https://doi.org/10.1016/j.tics.2013.06.006

Luo, L., Craik, F. I., Moreno, S., & Bialystok, E. (2013). Bilingualism interacts with domain in a working memory task: evidence from aging. *Psychology and Aging*, *28*(1), 28-34. https://doi.org/10.1037/a0030875

Marian, V., Bartolotti, J., Chabal, S., & Shook, A. (2012). CLEARPOND: Cross-Linguistic Easy-Access Resource for Phonological and Orthographic Neighborhood Densities. *PLoS One*, *7*(8), e43230. https://doi.org/10.1371/journal.pone.0043230

Morales, J., Calvo, A., & Bialystok, E. (2013). Working memory development in monolingual and bilingual children. *Journal of Experimental Child Psychology*, *114*(2), 187-202. https://doi.org/10.1016/j.jecp.2012.09.002

New, B. (2006). Lexique 3: Une nouvelle base de données lexicales. In *Actes de la Conférence Traitement Automatique des Langues Naturelles (TALN 2006)*.

Pierce, L. J., Chen, J. K., Delcenserie, A., Genesee, F., & Klein, D. (2015). Past experience shapes ongoing neural patterns for language. *Nature Communications*, *6*, 10073. https://doi.org/10.1038/ncomms10073

Pliatsikas, C. (2020). Understanding structural plasticity in the bilingual brain: The Dynamic Restructuring Model. *Bilingualism: Language and Cognition*, *23*, 459-471. https://doi.org/10.1017/S1366728919000130

Price, C. J. (2000). The anatomy of language: contributions from functional neuroimaging. *Journal of anatomy*, *197 Pt 3*(Pt 3), 335-359. https://doi.org/10.1046/j.1469-7580.2000.19730335.x

Ray, M. K., Mackay, C. E., Harmer, C. J., & Crow, T. J. (2008). Bilateral generic working memory circuit requires left-lateralized addition for verbal processing. *Cerebral Cortex*, *18*(6), 1421-1428. https://doi.org/10.1093/cercor/bhm175

Rottschy, C., Langner, R., Dogan, I., Reetz, K., Laird, A. R., Schulz, J. B., Fox, P. T., & Eickhoff, S. B. (2012). Modelling neural correlates of working memory: A coordinate-based meta-analysis. *NeuroImage*, *60*(1), 830-846. https://doi.org/https://doi.org/10.1016/j.neuroimage.2011.11.050

Silbert, N. H., Smith, B. K., Jackson, S. R., Campbell, S. G., Hughes, M. M., & Tare, M. (2015). Non-native phonemic discrimination, phonological short term memory, and word learning. *Journal of Phonetics*, *50*, 99-119. https://doi.org/https://doi.org/10.1016/j.wocn.2015.03.001

Sulpizio, S., Del Maschio, N., Fedeli, D., & Abutalebi, J. (2020). Bilingual language processing: A meta-analysis of functional neuroimaging studies. *Neurosci Biobehav Rev*, *108*, 834-853. https://doi.org/10.1016/j.neubiorev.2019.12.014

Vejnovic, D., Milin, P., & Zdravković, S. (2010). Effects of proficiency and age of language acquisition on working memory performance in bilinguals. *Psihologija*, *43*, 219-232. https://doi.org/10.2298/PSI1003219V

Wechsler, D. (2008). *WAIS-IV technical and interpretive manual*. The Psychological Corporation.