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Monolinguals and bilinguals respond differently to a delayed matching-to-sample task: An ERP study

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Abstract

Previous research examining whether bilinguals exhibit enhanced working memory (WM) compared to monolinguals has yielded mixed results. This inconsistency may be due to lack of sensitivity in behavioral and neuropsychological measures. The current study aimed to investigate the effects of bilingualism on WM by focusing on brain activity patterns (event-related potentials) in monolinguals and bilinguals during a WM task. We recorded brain activity while participants (26 monolingual English speakers and 28 English–French bilinguals) performed a delayed matching-to-sample task. Although performance measures were similar, electrophysiological differences were present across groups. Bilinguals exhibited larger P3b amplitudes than monolinguals, and smaller negative slow wave and N2b amplitudes during retrieval. These results suggest that bilinguals may have more cognitive resources available in WM to allocate to task completion, and that task completion may be less effortful for bilinguals than for monolinguals.

1. Introduction

Working memory (WM) is the system responsible for briefly storing and manipulating information that is no longer perceptually present (Baddeley, 2003; Diamond, 2012). WM consists of three major components: the central executive, the visuospatial sketch pad, and the phonological loop (Baddeley, 2003). The central executive controls the information that goes to the phonological loop and the visuospatial sketchpad, and determines which component will process the incoming information (Goldstein, 2014). The visuospatial sketch pad processes visual and spatial information (Baddeley, 2003), while the phonological loop is the subcomponent of WM that is responsible for the maintenance and temporary store of speech-based information (Atkins & Baddeley, 1998).

WM can be measured using various span tasks such as the Sternberg task (a delayed match-to-sample (DMS) task), backward digit span, sentence span, and serial recall of words (Baddeley, 2000; Gathercole & Pickering, 2000), because these tasks activate the phonological loop and articulatory rehearsal components of WM (Baddeley, 2000; Germano & Kinsella, 2005). WM has been associated with language comprehension (Cain, Oakhill & Bryant, 2004; Just & Carpenter, 1992): in complex span tasks, where the participant must follow a series of spoken instructions, people with high WM capacity can complete more of the spoken instructions than people with low WM capacity (Caplan & Waters, 1999). WM has also been related to word learning, and has been identified as a good predictor of the ability to learn a second language (Atkins & Baddeley, 1998; Service, 1992). The connection between WM and language was further indicated by a study demonstrating that people with a phonological loop deficit were unable to acquire a new language (Baddeley, Gathercole & Papagno, 1998). WM is thus associated with the ability to acquire a second language (Atkins & Baddeley, 1998). The present study investigates whether WM abilities differ in people who speak a second language compared to monolinguals.

Although some researchers have found no effect of bilingualism on WM (Blom, Küntay, Messer, Verhagen & Leseman, 2014; Engel de Abreu, 2011; Ratiu & Azuma, 2015), a recent meta-analysis found a larger WM capacity in bilinguals relative to monolinguals (small to medium effect size of 0.20) by comparing twenty-seven studies that examined WM capacity through various span tasks (Grundy & Timmer, 2017). Higher scores in WM span tasks support the view that bilinguals may exhibit improved WM capacity relative to monolinguals. While this bilingual effect has been shown in behavioral studies, few studies have examined whether neural activity during a WM task differs between monolinguals and bilinguals.

The processing of information in WM occurs rapidly, and behavioral measures such as RT have access to the cognitive state only after the response has occurred, meaning that the processes that led to the response can only be inferred. Event-related potentials (ERPs), in contrast, provide a millisecond-by-millisecond measure of the underlying neural processes associated with specific cognitive events, and may thus be more sensitive to fine-grained differences than behavioral measures alone. Indeed, a number of studies have found effects of bilingualism using ERP that were not detected behaviorally (Grundy, Anderson & Bialystok, 2017; Kousaie & Phillips, 2012; Morrison, Kamal & Taler, 2018). In the present study, we examined the neural differences in encoding and retrieval during a WM task in monolinguals and bilinguals, focusing on a number of ERP components that are associated with WM processing (P200, N2b, and P3b).

The P200 component is a fronto-central maximal positive waveform that peaks approximately 150–300 ms post-stimulus presentation (Luck, 2014). This component is thought to be related to attention allocation in WM processing (Lijffijt, Lane, Meier, Boutros, Burroughs, Steinberg, Moeller & Swann, 2009). In previous DMS tasks, the P200 has been measured during both encoding (Li, Tang & Chen, 2016; Pinal, Zurrón & Díaz, 2014, 2015) and retrieval (Broster, Jenkins, Holmes, Edwards, Jicha & Jiang, 2018; Li et al., 2016). During encoding, the P2 is not influenced by task difficulty (Li et al., 2016; Pinal et al., 2014), whereas during retrieval a decline in P2 amplitude is associated with decreased performance during the task being completed. More specifically, smaller P2 amplitudes during retrieval occur as a result of decreased attention allocation (Li et al., 2016) and lower WM performance (Finnigan, O'Connell, Cummins, Broughton & Robertson, 2011).

The N2b is a fronto-central negative waveform that occurs 200–350 ms following stimulus presentation (Folstein & Van Petten, 2008). This component is typically measured during conflict monitoring tasks (Veen & Carter, 2002), but is also reflective of stimulus detection and the ability to discriminate incongruities between stimuli (Bennys, Portet, Touchon & Rondouin, 2007; Folstein & Van Petten, 2008; Patel & Azzam, 2005). Similar to the P2, in a DMS task N2b amplitude is not modulated during encoding by task difficulty (Li et al., 2016; Pinal et al., 2014). However, during the retrieval phase of a WM task, N2b amplitude continually increases with task difficulty (Patel & Azzam, 2005; Pinal et al., 2014), indicating that as the task becomes more difficult, more attention and effort is needed to retrieve the memory of the past stimulus and discriminate the current stimulus from the previous one. During an n-back WM task, the N2b occurs later in low than high WM performers, indicating that low performers have a lower ability to detect and discriminate a stimulus than high performers (Daffner, Chong, Sun, Tarbi, Riis, McGinnis & Holcomb, 2011). However, during a DMS task, increased N2 latency is associated with higher performance (Pinal et al., 2015).

Lastly, the P3b peaks approximately 300–600 ms following stimulus presentation (Mertens & Polich, 1997; Polich, 2007). The P3b is one of the most widely studied components due to its involvement with multiple cognitive processes such as the updating of WM, cognitive control, memory processing, and attention (Donchin, 1981; Mertens & Polich, 1997; Polich, 2007). P3b amplitude reflects intensity of processing (Kok, 2001), and amplitude decreases are observed as task difficulty increases during retrieval (Kok, 2001; Polich, 1996) indicating decreases in the resources available to complete the task (Kok, 2001; Polich, 1996). Retrieval studies have also shown that, during a WM task, high performers have increased (rather than decreased) amplitudes as task difficulty increases, due to the availability of more resources for task completion (Daffner et al., 2011). Specific to DMS tasks, decreased P3b amplitude is shown in higher load conditions (Pinal et al., 2014) and in older adults (Pinal et al., 2015). These decreases in P3b amplitude with increasing task difficulty and age reflect decreases in the resources available for task processing and attentional allocation (Kok, 2001; Pinal et al., 2015; Polich, 1996).

Research is less consistent when examining P3b amplitude during encoding: some studies have shown decreases in amplitude with increased task difficulty (Pinal et al., 2014), while others show increases in amplitude as task difficulty increases (Studer, Wangler, Diruf, Kratz, Moll & Heinrich, 2010). This increase in amplitude during encoding would suggest that more resources are available to encode the information (Studer et al., 2010), whereas a decrease would suggest that fewer cognitive resources are available as task difficulty increases (Pinal et al., 2014). These conflicting findings may reflect the effects of reaching maximal capacity to perform the task: amplitude increases as the task becomes more difficult, but once maximal capacity is reached and performance plateaus, amplitude may then decrease because task completion requires more resources than are available.

The goal of the current study was to investigate whether bilinguals exhibit different neural activity during a WM task than monolinguals. Because WM is intimately linked with language function, including the ability to acquire a second language, we hypothesized that bilingualism might be associated with enhanced WM capacity and neural activity. To examine if differences are present between monolinguals and bilinguals, we had participants complete a DMS task while their EEG, accuracy, and reaction time were recorded. The present study was the first to use ERPs to examine the effects of bilingualism on WM encoding and retrieval processes during a DMS task. While differences in WM between these groups have been identified using behavioral and neuropsychological measures, neural processing differences remain unexplored. In line with previous research, we hypothesized that monolinguals and bilinguals would demonstrate similar accuracy and reaction time on the task. More efficient WM processing in bilinguals should be reflected in larger P2 and P3b amplitudes in bilinguals relative to monolinguals, indicating improved WM processing and ability to allocate attention during encoding and retrieval. N2b amplitude is expected to be smaller in bilinguals than monolinguals during retrieval, reflecting a greater ability to identify whether the test stimulus matches one from the memory set, and less effort expended to complete the discrimination.

2. Methods

2.1 Participants

Sixty-two young adults aged 18–30 were recruited through word of mouth at the University of Ottawa. Of the 62, eight were excluded for the following reasons: four participants had noisy data, requiring exclusion of more than 25% of their trials, and four participants responded with the wrong keys, so behavioral data was not recorded and ERPs could not be averaged. The remaining 54 participants were included in the study. There were 26 English monolinguals (16 females) and 28 bilinguals (20 females). The monolingual group had a mean age of 20.16 (±2.21) and 14.96(±1.77) years of education, while the bilingual group had a mean age of 20.54(±2.10) and 15.25(±1.76) years of education. Bilingual participants had a high proficiency in French and English and became fluent in both languages before the age of 13. Demographic information and neuropsychological test scores are provided in Table 1.

Table 1. Demographic and neuropsychological results by group (mean (SD))

	Group		
	Monolingual	Bilingual	t-test and *p*-values
N (females)	26(16 females)	28(20 females)	
Age	20.16(2.21)	20.54(2.10)	t(52)= −0.63, *p* = .53
Education	14.96(1.77)	15.25(1.76)	t(52)= −0.60, *p* = .55
Digit Span Forward	10.96(2.19)	11.29(2.66)	t(52)= −0.48, *p* = .63
Digit Span Backward	6.84(1.93)	7.86(2.52)	t(52)= −1.64, *p* = .10
Letter # Sequencing	11.16(2.08)	12.89(2.87)	t(52)= −2.49, *p* = .014*
WCST	4.24(1.16)	4.57(0.92)	t(52)= −1.55, *p* = .25
Stroop1	109.68(13.39)	109.57(17.79)	t(52)= 0.03, *p* = .98
Stroop2	81.00(10.90)	79.00(11.59)	t(52)= 0.65, *p* = .52
Stroop3	50.32(11.66)	53.75(11.57)	t(52)= −1.07, *p* = .28
Digit Symbol-Written	64.80(11.91)	65.92(10.22)	t(52)= −0.37, *p* = .71
Digit Symbol-Oral	70.15(10.65)	76.00(13.77)	t(52)= −1.74, *p* = .08
BNT-English (/60)	53.04(3.34)	50.18(7.61)	t(52)= 1.70, *p* = .09
FAS Fluency- English	39.62(9.08)	41.79(13.94)	t(52)= −0.67, *p* = .51
FAS Fluency- French		28.24(10.03)	
BNT-French (/60)		36.82(10.02)	

Notes: BNT = Boston Naming Test, WCST = Wisconsin Card Sorting Test (categories completed). Stroop1 = requires participants to read name of colors, Stroop2 = name the color of "X's", Stroop3 = name the ink color of color words printed in a different color (e.g., the word "RED" printed in green ink). Digit Symbol-Written = match the digit to corresponding symbol by writing the answer, Digit Symbol-Oral = match the digit to corresponding symbol by reading the answer aloud. FAS fluency is a controlled oral word association test to assess word fluency.

All participants first completed a health questionnaire to ensure they had no history of neurological or psychiatric conditions, were not taking medications that influence the central nervous system or cognitive functioning, had not suffered any major head injuries, and were right-handed. Additionally, participants were asked to complete a self-rated language proficiency scale for all languages they knew (in listening, reading, speaking, and writing); bilinguals also completed a language history and usage questionnaire to assess their language usage frequency (Table 2). In the monolingual group, 10 of the 26 participants had no French abilities, with the rest having a basic understanding of common terms. This basic knowledge was gained throughout their education in elementary school as part of the Ontario School Board curriculum.

In Ontario, students are required to take mandatory core French from grade 4 until grade 9. Each student must have 600 hours of French instruction, which are divided into approximately 3.3 hrs. a week of French instruction from grade 4 to grade 8 (Ontario Ministry of Education, 2013). Additionally, students are only required to take one French class in grade 9 (Ontario Ministry of Education, 2014). Overall, exposure to French in Ontario is low: the English–French bilingualism rate is only 11% (Statistics Canada, 2017), with only 37.6% of Ottawa residents being English–French bilingual in 2016 (Statistics Canada, 2019). The monolingual participants never obtained fluency in French and operate solely in English; therefore, no values were given (in Table 2) for their percentage of use in French at home, school, or work. In addition, participants were excluded if they reported knowledge of another language rated at or above a 3 ("moderate ability"), and if monolinguals reported a knowledge of French at or above a 3 they were also excluded. The study was approved by the research ethics board at Bruyère Research Institute; participants provided informed written consent before starting the study and were compensated $10 an hour.

2.2 Procedure

Participants completed two testing sessions, each lasting approximately 1 to 1.5 hours. The first session consisted of a neuropsychological battery to assess language proficiency, executive functions, and WM functioning. To test working memory, the battery included three subtests of the Wechsler Memory Scale (WMS-III) (Wechsler, 1997): letter-number sequencing, in which participants hear a series of numbers and letters and repeat them in increasing numeric and alphabetic order; and digit span, in which participants hear a series of numbers and repeat them back in the same order (forward digit span) or in reverse order (backward digit span). To test processing speed, participants completed the written and verbal Digit Symbol Substitution subtest of the Wechsler Adult Intelligence Scale-III (WAIS-III) (Wechsler, 1997), in which they must match digits to their corresponding symbols as quickly as possible. To test inhibitory function, participants completed a version of the Stroop task (Stroop, 1935), where they had one minute to name as many items as possible in the three conditions (color naming, word reading, and interference conditions). Executive functions were assessed using the Wisconsin Card Sorting Test (Grant & Berg, 1948), where participants must sort a deck of 64 cards according to color, shape, and number based on four different category sorting cards. The participants were not told how to sort the cards, but were told whether their sorting was correct or incorrect. After 10 consecutive correct sorts in a given category, the category was switched. Verbal fluency was assessed using letter (FAS) criteria (Borkowski, Benton & Spreen, 1967). Finally, participants completed the Boston

Table 2. Relative use of language and self-reported proficiency ratings.

	Monolinguals	Bilinguals	t-test & *p*-value
French Age of Acquisition	6.06 (1.56)	4.57(2.70)	t(44) = 2.07 *p* = .024*
French Age of Fluency	—	10.32(3.30)	
English Proficiency Rating			
Listening	4.92(0.27)	4.93(0.26)	t(52)=−0.16, *p* = .80
Reading	5(0)	4.93(0.26)	t(52) = 1.33, *p* = .19
Speaking	5(0)	4.93(0.26)	t(52) = 1.33, *p* = .19
Writing	4.96(0.20)	4.93(0.26)	t(52) = 0.45, *p* = .65
French Proficiency Rating			
Listening	1.70(0.46)	4.54(0.51)	t(52)=−20.96, *p* < .001*
Reading	1.70(0.55)	4.50(0.51)	t(52)=−18.99, *p* < .001*
Speaking	1.67(0.48)	4.39(0.50)	t(52)=−20.00, *p* < .001*
Writing	1.54(0.51)	3.96(0.74)	t(52)=−13.46, *p* < .001*
French use at home			
Speaking	—	32.14% (40.74)	
Listening to speak	—	36.61% (35.01)	
Reading	—	26.78% (28.13)	
Writing	—	25.89% (27.62)	
French use at school/work:			
Speaking	—	36.61% (24.04)	
Listening to speak	—	40.18% (22.91)	
Reading	—	32.14% (21.36)	
Writing	—	30.57% (21.90)	

Note: Values reported are mean scores with standard deviations. Self-rated proficiency was rated on a five-point scale: 1-no ability at all, 2-Very little ability, 3-Moderate ability, 4-Very good ability, 5-Native-Like abilities. Language use was rated on a 5-point scale: 0%, 25%, 50%, 75%, and 100% of the time. Age of acquisition is reported for monolingual speakers because many received French instruction in school but never achieved fluency.

Naming Test (BNT, (Kaplan, Goodglass, Weintraub & Segal, 1983), where they were asked to name a series of 60 line drawings of increasing difficulty. Bilingual participants completed the fluency tasks and BNT in both English and French to allow us to determine their level of proficiency in both languages. During the second session the participants completed the DMS task while their EEG, accuracy, and reaction time were recorded.

2.3 Delayed Match-to-Sample Task

This task consists of three different conditions (low, medium, and high WM load). In each condition the participant first sees a fixation cross for 1000ms, followed by an array of numbers to store in memory (which varies in time between conditions; explained below), a retention period of 500ms, and then a test array for 1500ms where they must indicate if the number matches one of the numbers shown in the memory array. The memory array duration increased with set size. For condition 1 (low memory load) the participant is shown one digit for 1200ms, in condition 2 (medium memory load) the participant is shown three digits for 3600ms, and in condition 3 (high memory load) the participant is shown 5 digits for 6000ms (See Figure 1). For all conditions, participants responded yes by pressing the “A” key and no by pressing the “L” key on the keyboard. Each condition consisted of 120 trials; trials were equally balanced between yes and no responses.

2.4 EEG data recording and analysis

EEG was recorded from 32 sites across the scalp using active silver-silver chloride electrodes attached to an electrode cap (Brain Products, GmbH, Munich, Germany) placed according to the international 10–20 system. Vertical eye movements and blink artifacts were recorded through an electrode placed on the infraorbital ridge of the left eye to monitor eye blinks (vertical EOG), to be removed during data cleaning. All impedances were kept below 20 kΩ and the EEG was digitized at a rate of 500Hz with a time constant of 2 s. FCz was used as the reference during recording, but a new reference was generated offline using an average of both mastoids and was used as a reference for all channels.

The data were reconstructed using Brain Products’ Analyzer software (Brain Products, GmbH, Munich, Germany). The EEG was down-sampled to 250Hz, then digitally filtered using a low pass filter of 30 Hz and a high pass filter of 0.1 Hz. Next, the EEG was visually inspected for channels that contained high levels of noise. These channels were replaced by interpolating the data of surrounding electrode sites (Perrin, Pernier, Bertrand, Echallier, Inserm, Thomas & France, 1989). Vertical EOG was computed by subtracting activity from FP1 from that of the EOG placed on the infraorbital ridge of the left eye. Horizontal eye movement was computed by subtracting F7 activity from that of F8. Independent Components Analysis was used to identify and

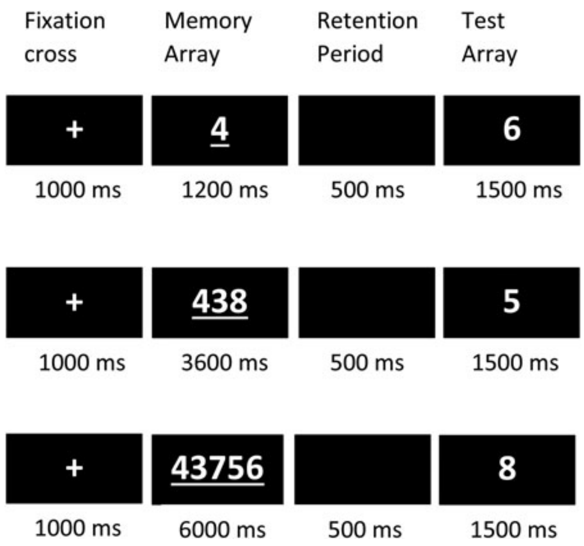

Fig. 1. Description of the task: an example of the stimuli used for each condition and timing of stimulus presentation. In all examples shown above participants would respond “no” by pressing the “L” key to state that the probe does not match the memory array.

remove eye movements and blink artifacts that were statistically independent of the EEG activity (Makeig, Bell, Jung & Sejnowski, 1996). The EEG was reconstructed into 1200 ms epochs beginning 200 ms before stimulus onset. The 200 ms pre-stimulus period served as a zero-voltage baseline period. Any epochs containing EEG activity exceeding ±100 µV were rejected from the averaging, with only correct trials included in averages.

3. Statistical Analysis and results

3.1 Neuropsychological data

All statistical analyses were conducted using the Statistical Package for the Social Science for Windows v.22 (SPSS inc., Chicago, IL, USA). Neuropsychological test scores between groups were compared using an independent sample t-test and corrected for multiple comparisons with Bonferroni correction using an alpha of 0.05. There were no significant differences between monolinguals and bilinguals on English-language performance in any of the language or fluency tasks. Bilinguals had significantly higher scores (12.89 ± 2.87) than monolinguals (11.16 ± 2.08, $p = .014$) on the letter-number sequencing WM task.

A repeated-measures ANOVA was used to analyze bilingual participants’ self-rated English and French proficiency, performance in English and French on all fluency measures, and BNT. Bilinguals’ self-rated proficiency was significantly higher for listening, reading, writing, and speaking in English compared to French ($p < .001$). Their performance in the FAS language fluency task was also higher in English than in French, indicating that our bilingual participants were English-dominant (FAS English: 41.79 ± 13.94; FAS French 28.21 ± 10.04, $p < .001$). Additionally, a one-way ANOVA comparing means for monolinguals and bilinguals in Listening, Reading, Speaking, and Writing in English and French as well as Age of Acquisition of French revealed that monolinguals and bilinguals did not differ in their English proficiency (all analyses $p > .005$). However, as expected, bilinguals had higher self-rated proficiency in all French measures than monolinguals (See Table 2).

Table 3. Behavioral performance on the delayed match-to-sample task for each condition and group.

Measures for DMS Mean (Standard Deviation)	Group Monolinguals (n = 25)	 Bilinguals (n = 28)
1 number		
RT (ms)	621.12(101.72)	587.45(120.47)
Accuracy (%)	94.36(2.02)	93.91(3.34)
Omissions (#)	2.72(0.89)	3.39(1.26)
Commissions (#)	1.00(1.22)	1.14(1.33)
3 numbers		
RT (ms)	742.32(120.47)	717.19(144.53)
Accuracy (%)	94.31(4.10)	94.68(3.29)
Omissions (#)	0.52(0.71)	0.64(0.73)
Commissions (#)	2.04(2.94)	1.79(1.93)
5 numbers		
RT (ms)	796.18(124.69)	775.37(136.37)
Accuracy (%)	92.67(5.53)	90.75(8.35)
Omissions (#)	1.16(1.43)	1.21(1.47)
Commissions (#)	3.32(3.23)	3.39(3.90)

Notes: Values given are means with standard deviations. A total of 26 monolinguals took part in the study; however, one monolingual’s behavioral data was lost due to computer error.

3.2 Delayed match-to-sample task behavioral performance

Trials with reaction times (RTs) more than ±2.5 standard deviations from the mean by participant and condition were excluded as outliers. Outliers comprised under 1% of all trials in all conditions and groups. Accuracy and RT were analyzed using separate 2 × 3 mixed ANOVAs with group (Monolingual vs. Bilingual) as the between-subjects factor and Condition (low-, medium-, high-load) as the within-subjects factor.

The repeated measures ANOVA revealed that accuracy did not differ from low load (94.13%) to medium load (94.50%, $p = 1.00$), but did differ between low load and high load (94.13% vs 91.51%, $p < .001$), and between medium load and high load ($p < .001$) (main effect of Condition, $F(2,102) = 13.53$, $p < .001$, $\eta_p^2 = 0.28$). Reaction time also increased with task difficulty; low load elicited the shortest reaction time (604.29 ms), followed by medium load (729.76 ms), then high load (785.77 ms), and all conditions significantly differed ($p < .001$), as shown by a main effect of Condition, $F(2,102) = 221.71$, $p < .001$, $\eta_p^2 = 0.81$). There were no accuracy nor reaction time differences between monolingual and bilingual groups (behavioral data are shown in Table 3).

3.3 ERP analyses

Peak measurement was used to obtain peak P2 and N2b amplitude and latency and mean area was used to measure P3b amplitude. For P2 and N2b amplitude and latency and P3b amplitude, separate analyses were run using a 3 × 3 × 2 mixed model ANOVAs. The within-subjects factors were ROI (frontal, fronto-central, central) and Condition (low, medium, high load), and the between-subjects factor was Group (Monolingual vs. Bilingual). The frontal ROI included F3, Fz, and F4, the fronto-central

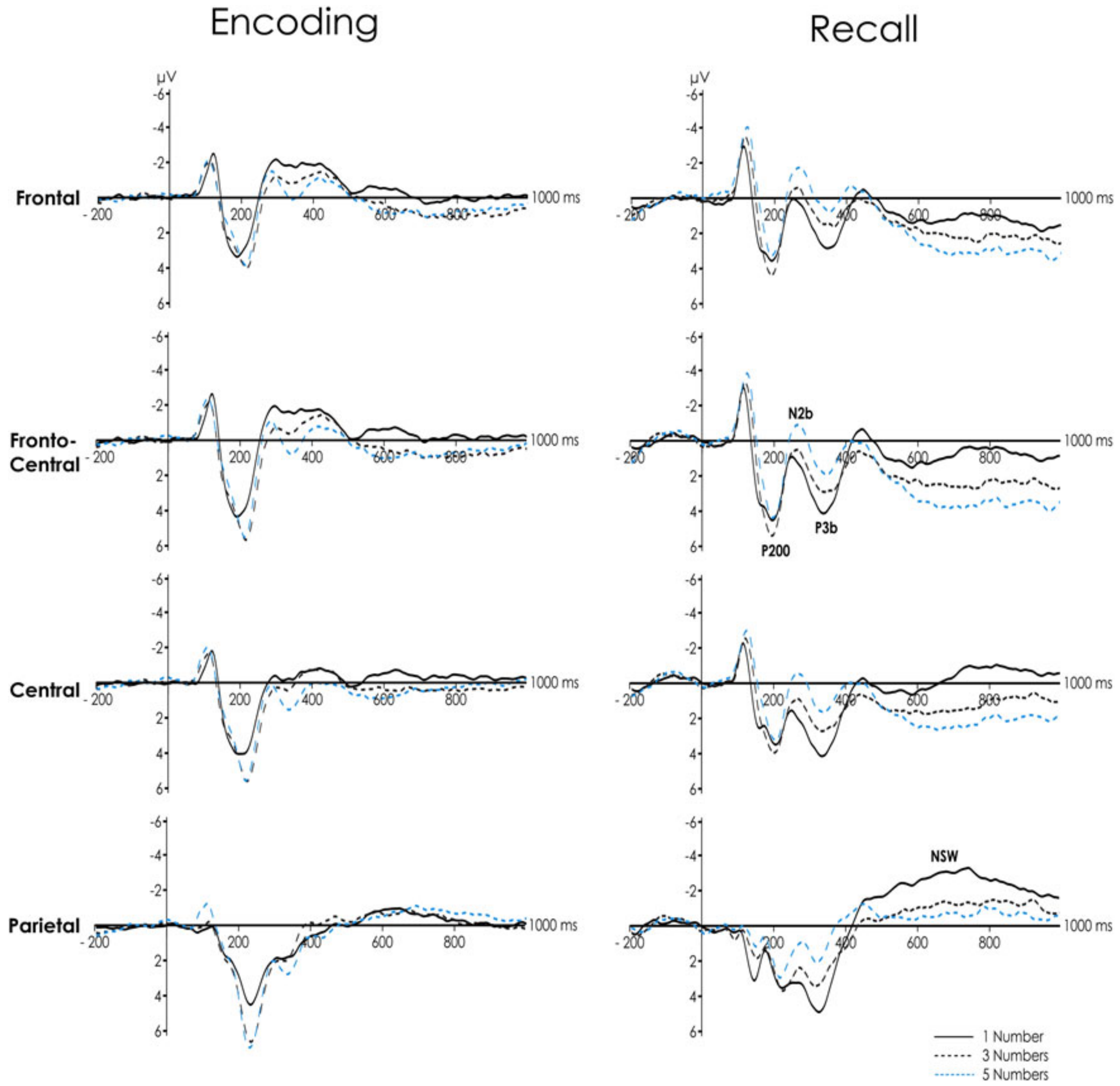

Fig. 2. Grand averaged ERP waveforms collapsing across groups to show the effects of condition during encoding and retrieval. Averages at frontal (F3, Fz, F4), fronto-central (FC1, FCz, FC2), central (C3, Cz, C4), and parietal (P3, Pz, P4) regions are shown. Negative is plotted up.

ROI included FC1, FCz, and FC2, and the central ROI included C3, Cz, and C4. After visual inspection, the negative slow wave (NSW) component appeared to differ due to task condition during retrieval and therefore was also analyzed using a 3 × 2 mixed ANOVA with the within-subjects factor of Condition (low, medium, high load), and the between-subjects factor of Group (Monolingual vs. Bilingual) at the averaged parietal regions (P3, Pz, P4)

3.3.1 Encoding

Two components were selected for analysis during the encoding phase: the P2 and the P3b. The P2 was measured from 150–300 ms and the P3b was measured from 250–450 ms post-stimulus. Effects of task difficulty are shown in Figure 2, and language differences during encoding are shown in Figure 3.

No main effects of group nor interactions were observed on the amplitude of the P2 component. Medium load elicited the largest amplitude (6.24 μV), followed by high load (5.94 μV), and then low load (5.32 μV). However, the only significant difference was between low load and medium load ($p = .003$) (main effect of Condition, $F(2,104) = 3.75$, $p = .009$, $n_p^2 = 0.10$). Similarly, low load elicited a shorter P2 latency (193.69 ms) than high load (202.25 ms, $p = .013$), (main effect of Condition $F(2,104) = 3.75$, $p = .027$, $n_p^2 = 0.07$).

The P3b analysis revealed a main effect of condition, with a more positive amplitude in high (−0.14 μV) than low (−0.52 μV, $p < .001$) and medium load (−1.20 μV, $p = .008$), with medium load also eliciting a larger amplitude than low load ($p < .001$) (main effect of Condition, $F(2,104) = 20.63$, $p < .001$, $n_p^2 = 0.28$). That is, as task difficulty increased from low to high load the amplitude increased. There was also a trend for bilinguals to exhibit larger (−0.24 μV) P3b amplitudes than monolinguals (−1.06 μV) (main effect of Group, $F(1,52) = 3.83$, $p = .056$, $\text{n}_\text{p}^2 = 0.08$).

3.3.2 Retrieval

Three components were selected for analysis during the retrieval test phase: the P2, N2b and P3b. However, after visual inspection of the waveforms it was determined that NSW appeared to vary

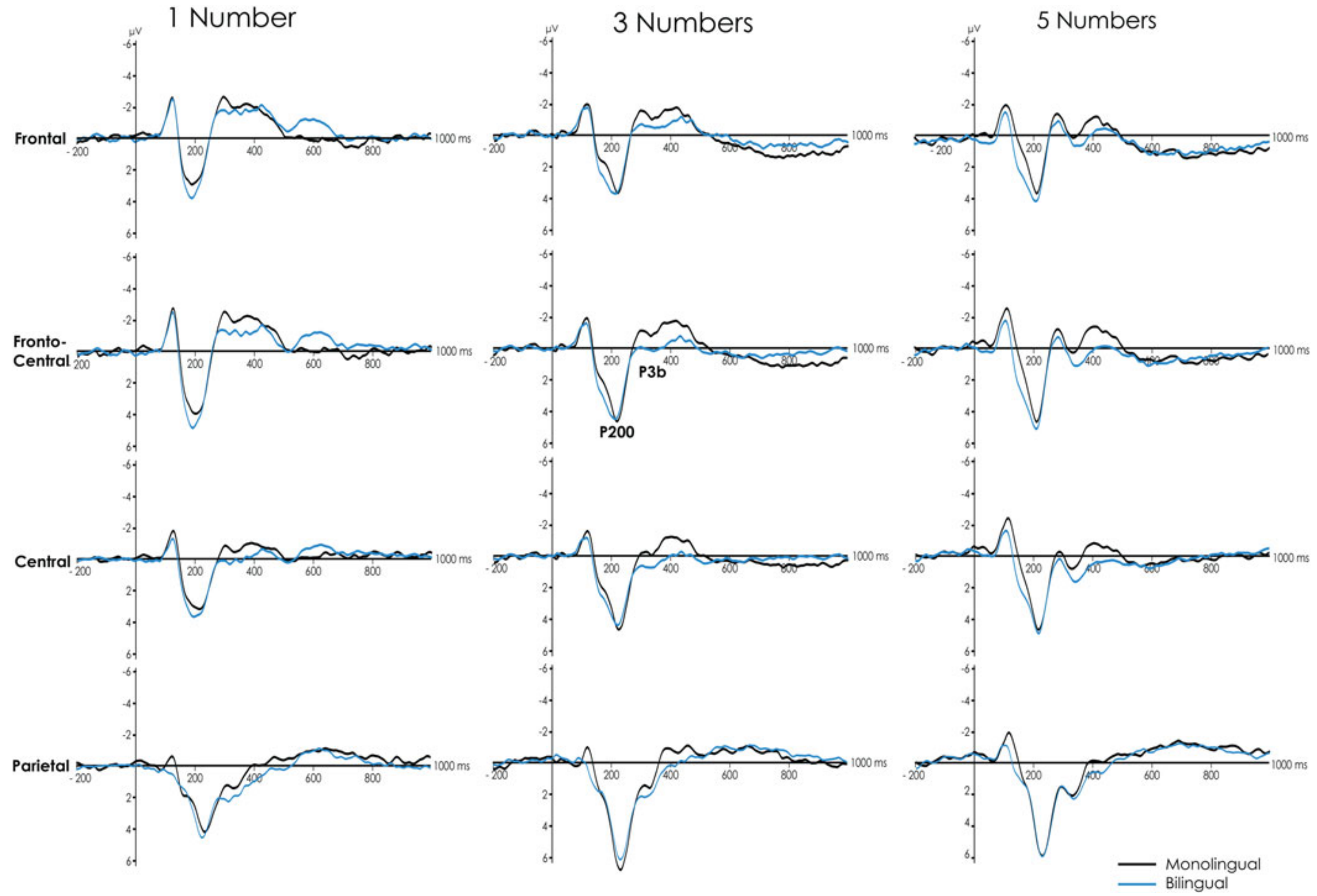

Fig. 3. Grand averaged ERP waveforms for monolingual and bilingual young adults during encoding for each of the conditions. Bilinguals exhibited larger P3b amplitudes than monolinguals, while P200s were similar in the two groups.

between groups and conditions, and this component was thus also selected for analysis. The P2 was scored as the most positive peak from 150–300 ms and the N2b was scored as the most negative peak from 200–350 ms. After visual inspection of the P3b, it was determined that no distinct peak was present. Mean amplitudes were calculated at frontal, fronto-central, and central regions with a time window of 250–450 ms. The NSW mean amplitude was calculated in the parietal regions (P3, Pz, and P4) from 500–800 ms. Condition effects during retrieval are shown in Figure 2, and language group differences are shown in Figure 4.

The P2 analysis revealed that amplitude decreased with task difficulty, with high load eliciting significantly smaller amplitudes (4.41 μV) than low (5.47 μV, $p = .001$) and medium load (5.53 μV, $p < .001$), (main effect of task difficulty, $F\ (2,104) = 11.92$, $p < .001$, $n_p^2 = .19$). There were no significant differences in P2 latency due to group or condition or in P2 amplitude due to group.

N2b amplitude was significantly smaller in bilinguals (−1.06 μV) than monolinguals (−2.49 μV) (main effect of Group, $F\ (1,52) = 5.39$, $p = .024$, $n_p^2 = 0.09$). Amplitude increased with increasing task difficulty (main effect of task difficulty, $F(2, 104) = 14.15$, $p < .001$, $n_p^2 = 0.21$). High load elicited a larger amplitude (-2.58 μV) than medium (-1.69 μV, $p = .003$) and low load (-1.35 μV, $p < .001$). The only N2b latency effect was due to task difficulty, where high load elicited a longer latency (285.17 ms) than low and medium load, although this effect only reached statistical significance for low load (265.70 ms, $p = .037$), (main effect of Condition, $F(2,\ 104) = 4.38$, $p = 0.019$, $n_p^2 = 0.08$). There were no N2b latency effects due to language.

Monolinguals showed smaller P3b amplitudes (0.20 μV) compared to bilinguals (1.67 μV), (main effect of Group, $F(1,52) = 5.41$, $p = .024$, $n_p^2 = 0.10$). The P3b also declined in amplitude with increasing task difficulty. That is, high load elicited significantly smaller amplitudes (0.09 μV) than low (1.60 μV, $p < .001$) and medium load (1.11 μV, $p = .001$) (main effect of Condition, $F(2,104) = 14.06$, $p < .001$, $n_p^2 = 0.22$).

As shown by a main effect of Group $F\ (1,52) = 8.41$, $p = .005$, $n_p^2 = 0.14$, bilinguals exhibited a more negative (−1.94μV) NSW than monolinguals (−0.52 μV). Task difficulty also influenced the NSW, which became more positive with increasing task difficulty. All conditions significantly differed in amplitude ($p < .025$), with high load eliciting the smallest SW (−0.43 μV), followed by medium load (−0.86 μV) and low load (−2.37 μV), (main effect of Condition, $F(2,104) = 12.49$, $p < .001$, $n_p^2 = 0.39$).

4. Discussion

The present study aimed to investigate the differences in neural activity between monolinguals and bilinguals during a WM task, the delayed match to sample (DMS) task. We examined brain activity patterns during both encoding and retrieval, and found that

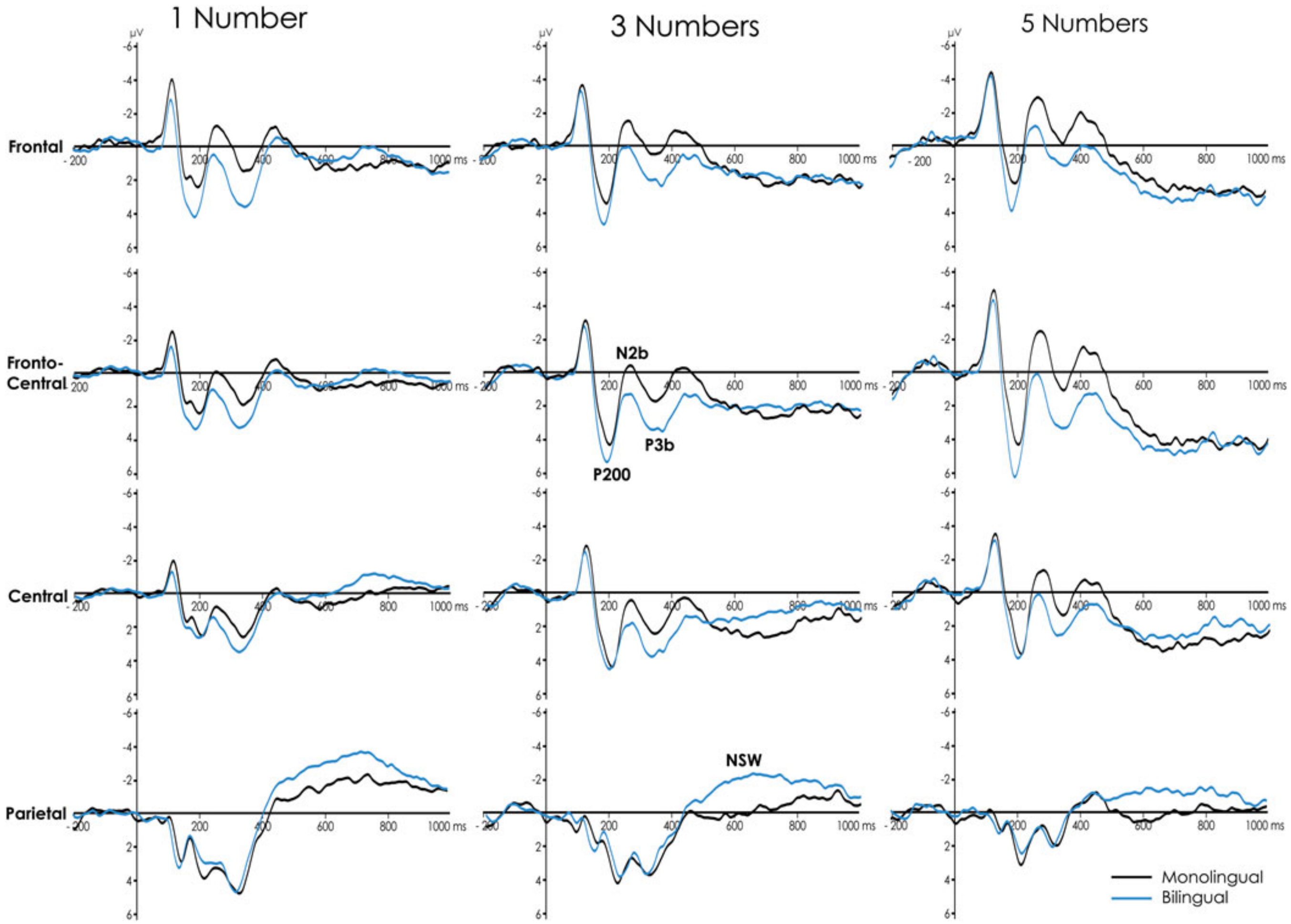

Fig. 4. Grand averaged ERP waveforms for monolingual and bilingual young adults during retrieval for each of the conditions. Bilinguals exhibited smaller N2b and NSW amplitudes and larger P3b amplitudes than monolinguals.

bilinguals exhibited larger P3b amplitudes during retrieval but only showed a trend for larger amplitudes during encoding. Furthermore, bilinguals exhibited smaller N2b and NSW amplitudes than monolinguals during the retrieval phase, suggesting that task completion may be easier for bilinguals than monolinguals. Electrophysiological differences between monolinguals and bilinguals were observed in the absence of differences in behavioral performance, suggesting that ERPs may be more sensitive to differences in cognitive processes than behavioral measures.

4.1 Encoding

Both WM load and language group exerted an effect on ERP response during the encoding phase. With respect to WM load, P200 amplitude was larger in the low- than the medium-load condition, with no difference between the medium- and high-load conditions, suggesting that the high-load condition may not have required additional attention for stimulus encoding relative to the medium-load condition. P200 latency was longer in the high-load condition than in the low-load condition, indicating the need for more processing time in the more difficult conditions. Previous studies have found no effect of task difficulty on the P200 (Li et al., 2016; Pinal et al., 2014). These conflicting findings may be due to differences in stimulus presentation: Li et al. (2016) presented letters for 2000 ms whereas Pinal and Diaz, 2014 presented domino images for 1000 ms, and both studies presented all stimuli for the same time independent of memory load. Our study presented numbers, which varied in duration depending on the memory load (low load: 1200 ms, medium load: 3600 ms, and high load: 6000 ms). Previous research has found that different task requirements can generate different neural responses even if the same cognitive process is being measured (Pfefferbaum, Wenegrat, Ford, Roth & Kopell, 1984).

Past research examining the P3b during encoding has been inconsistent, with one study reporting increased amplitude due to high memory load (Studer et al., 2010) and another reporting decreased amplitude with high memory loads (Pinal et al., 2014). We found that the P3b increased in amplitude during encoding as task difficulty increased, suggesting that a larger P3b is elicited in the high-load condition because more attentional resources are allocated to memorize the numbers (Kok, 2001; Studer et al., 2010). Thus, this finding suggests that our participants may have focused more attention on the more difficult trials, resulting in more resources being allocated during encoding to the high-load (5-number) condition (Studer et al., 2010). The difference in P3b amplitude between monolinguals and bilinguals did not reach significance; future research should explore this finding further to examine the possibility that bilinguals may have more attentional resources available to encode the numbers presented compared to monolinguals.

4.2 Retrieval

As in encoding, both language and WM load influenced the P2, N2b, and P3b during retrieval. P2 amplitude decreased as task difficulty increased, indicating a reduced ability to allocate the required attention to complete the task (Finnigan et al., 2011; Li et al., 2016; Lijffijt et al., 2009). The N2b became more negative (larger) as task difficulty increased, with the greatest difference between the low- and high-load conditions. This finding is consistent with previous research indicating that the N2b becomes more negative with increasing task difficulty because more cognitive processes are required to complete the task (Patel & Azzam, 2005) and there is a decrease in the ability to determine if the target matches the stimulus held in memory (Bennys et al., 2007; Patel & Azzam, 2005). Finally, P3b amplitude decreased as a result of task difficulty, with the high-load condition eliciting smaller P3b amplitude than the low- and medium-load conditions. These differences indicate that with increasing task difficulty, fewer resources were available to allocate to successful task completion.

Effects of language group provide evidence that monolinguals and bilinguals have different neural activation patterns for a DMS WM task. N2b amplitudes were smaller in bilinguals than monolinguals, suggesting that bilinguals expend less effort than monolinguals to focus attention on the task and determine whether the target stimulus was present in the memory array (Bennys et al., 2007; Folstein & Van Petten, 2008).

Effects of language group were also observed during retrieval. Bilinguals exhibited a larger P3b amplitude than monolinguals across all conditions. This finding is consistent with our previous study reporting larger P3b amplitudes in bilinguals than monolinguals across all conditions in an n-back WM task (Morrison et al., 2018). Larger P3b amplitudes in bilinguals than monolinguals suggest that bilinguals have more resources available to complete the task (Daffner et al., 2011; Kok, 2001). Previous research in high- and low-performing adults found that high performers exhibited larger P3b amplitudes than low performers due to the availability of more resources (Daffner et al., 2011). Similarly, bilinguals exhibited larger amplitudes than monolinguals, and therefore should have had higher performance than monolinguals (Daffner et al., 2011). Despite decreased amplitude with increasing task load in both groups, monolinguals and bilinguals had enough resources available to complete the task effectively, as indicated by high accuracy in all conditions. Therefore, although bilinguals had larger overall P3b amplitudes, determining whether the availability of more resources in bilinguals translates to a behavioral advantage was not possible.

Previous studies have found this negative-going wave during a spatial and object WM task (Mecklinger & Pfeifer, 1996), a verbal WM task (Ruchkin, Grafman, Krauss, Johnson, Canoune & Ritter, 1994), and the Sternberg WM task (Axmacher, Lenz, Haupt, Elger & Fell, 2010; Axmacher, Mormann, Cohen & Elger, 2007; Kleen, Testorf, Roberts, Scott, Jobst, Holmes & Lenck-Santini, 2016). This negative activity tends to occur between 400 and 1200 ms post-stimulus presentation and is largest in the occipital and parietal areas (Mecklinger & Pfeifer, 1996; Ruchkin et al., 1994). The NSW varies in amplitude with WM load (Axmacher et al., 2010, 2007; Kleen et al., 2016; Mecklinger & Pfeifer, 1996; Ruchkin et al., 1994) suggesting that this component reflects cognitive processes involved with WM. Coinciding with past research on ERPs during a Sternberg task (Kleen et al., 2016), we found that the NSW decreased with increased task difficulty, and that monolinguals exhibited smaller amplitudes than bilinguals across all conditions.

A decline in NSW amplitude with higher task difficulty was also reported in previous studies (Kleen et al., 2016; Mormann, Fell, Axmacher, Weber, Lehnertz, Elger & Fernández, 2005). This component has been related to the resources needed to process the features of the stimuli (Mecklinger & Pfeifer, 1996) with changes in amplitude reported with increasing task difficulty due to additional processing needed to make a decision (Ruchkin & Sutton, 1983). Taken together with our finding that monolinguals exhibited smaller negative amplitudes than bilinguals, this finding suggests that monolinguals have fewer resources available to process the stimuli being presented. Unfortunately, because accuracy and reaction time did not differ between groups in our study, we could not correlate the NSW with behavioural measures as has been done in previous studies (Kleen et al., 2016). Future research should replicate this study with a more difficult task in order to see if the neural activity exhibited by bilinguals translates into a behavioral advantage under more challenging task conditions. Additionally, although all the ERP components examined here are associated with WM processing, between-group differences could be due to other external factors such as motivation and attention, which were not the focus of this study. However, because group differences were only revealed in the retrieval phase, we argue that the reported differences between monolinguals and bilinguals do reflect differences in WM processing.

4.3 Behavior

Behaviorally, decreased accuracy and increased reaction time were observed in response to higher task difficulty in both monolinguals and bilinguals. Group differences in DMS performance may not have been observed in the present study because both groups performed near ceiling across all three conditions (accuracy > 90%). Future research should examine whether group differences in behavioral performance may be observed with a larger sample size. The performance of monolinguals and bilinguals differed in the letter-number sequencing task, which is considered an accurate measure of WM because it requires participants to not only retrieve stimuli presented but also manipulate the information during retrieval (Diamond, 2012). Ceiling effects are not observed in this task because testing is continued until the participant gets a number wrong, enabling us to obtain an accurate measurement of each participant's WM capacity. Our finding of higher WM capacity in bilinguals is consistent with previous research indicating that bilingualism is associated with larger WM capacity compared to monolinguals (Kudo & Swanson, 2014; Morales, Calvo & Bialystok, 2013), including a recent meta-analysis showing larger WM capacity in bilinguals during a span task (Grundy & Timmer, 2017). Higher WM during a span task suggests that bilinguals have a higher WM capacity than monolinguals.

One possibility is that people with higher WM capacity are more likely to become bilingual. However, given the background of the participants in the present study, we consider this explanation unlikely. The bilingual speakers were exposed to French and English from a young age, with French exposure typically occurring in the home (Franco-Ontarians constituting a large minority population in the province) and English exposure occurring in school and other external contexts. Under such circumstances, monolingualism is highly unusual. Monolinguals were typically exposed to only English in both home, school, and external contexts. Thus, the monolingual participants in this study are fluent in only one language due to environmental exposure, rather than inability to learn a second language.

5. Conclusion

In sum, we found that bilinguals exhibited higher WM capacity than monolinguals in the letter-number sequencing WM task, despite the two language groups exhibiting similar accuracy and reaction time on the DMS task. The ERP findings confirm that differences in WM performance between monolinguals and bilinguals are due to cognitive processing differences during retrieval. Bilinguals also exhibited a larger P3b than monolinguals during retrieval, suggesting that they have more resources available to use when task difficulty increases. Smaller N2b and NSW amplitudes in bilinguals imply that task completion requires less effort for bilinguals than monolinguals. Overall, these findings suggest that bilingualism is associated with enhanced WM functioning, as demonstrated by larger WM capacity and differing neural activity during WM tasks.

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