Neuropsychologia 143 (2020) 107468

Contents lists available at ScienceDirect

Neuropsychologia

journal homepage: http://www.elsevier.com/locate/neuropsychologia

ERP measures of the effects of age and bilingualism on working memory performance

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ARTICLE INFO

Keywords:
Bilingualism
Event-related potentials
Working memory
Delayed match-to-sample
Age differences

ABSTRACT

Previous research has suggested that bilinguals may exhibit cognitive advantages over those who are monolingual, although conflicting results have been reported. This advantage may be heightened in older adults, because of age-related cognitive decline. However, the effects of bilingualism on working memory performance in older adults remain unknown. The current study uses electroencephalography to measure brain activity (event-related potential; ERP) differences between young and older monolinguals and bilinguals during a delayed matching-to-sample task. Although there were no effects of bilingualism in behavioral measures, differences were observed in electrophysiological measures. While no Age by Language interaction was observed, several main effects were identified. Compared to young adults, older adults exhibited smaller N2 amplitudes and larger P2 and P3b amplitudes in the medium and high load conditions. Older adults also displayed an increased slow wave amplitude that occurred in conjunction with increased reaction time. ERP differences during difficult tasks in older adults suggest the use of compensatory mechanisms to maintain similar performance to the young adults. Bilinguals exhibited smaller N2 and larger P2 and P3b amplitudes than monolinguals. ERP differences observed in bilinguals may reflect differences in cognitive processing. However, in the absence of performance differences between monolinguals and bilinguals, interpreting a bilingual advantage in working memory processing is difficult.

1. Introduction

Over half of the world's population is fluent in more than one language (Costa, 2005). Researchers have focused on potential cognitive advantages related to bilingualism, as well as whether these advantages can help mitigate age-related cognitive decline. The bilingual advantage is typically described in terms of bilinguals' superiority in behavioral performance (i.e., improved performance and reaction time) relative to monolinguals. However, evidence for a bilingual cognitive advantage has generated inconsistent findings in a variety of cognitive domains including cognitive control, task switching, and inhibitory processes (for a review see Adesope et al., 2010; Lehtonen et al., 2018).

Initial findings suggested that the bilingual advantage was evident in performance measures during problem-solving and creativity tasks (Bain, 1975; Kessler and Quinn, 1987; Peal and Lambert, 1962). More recent research reports performance advantages on a variety of executive functions, including inhibition (Badzakova-Trajkov, 2008; Bialystok et al., 2008; Carlson and Meltzoff, 2008) and task switching (Prior and Gollan, 2011). Nevertheless, some studies have reported no bilingual advantage on tasks including those measuring inhibitory processing (Duñabeitia et al., 2014; Kousaie and Phillips, 2017; Rosselli et al., 2002), conflict monitoring (Gathercole et al., 2014), or executive functioning (Goldman et al., 2014). One study measuring 15 different indicators of executive processing found no group differences between monolinguals and bilinguals in the performance of executive function tasks (Paap and Greenberg, 2013).

One cognitive domain in which the effect of bilingualism remains particularly controversial is working memory. Working memory involves temporary storage and manipulation of a memory representation (Baddeley, 2012). Research on the effects of bilingualism on working memory performance has generated inconsistent results, with some studies reporting enhanced working memory performance in bilinguals (e.g., Kudo and Swanson, 2014; Morales et al., 2013), and others reporting no advantage (Blom et al., 2014; Bonifacci et al., 2011; Engel de Abreu, 2011; Ratiu and Azuma, 2015). However, a recent meta-analysis found that bilinguals exhibit a larger working memory capacity than monolinguals during a span task (Grundy and Timmer, 2017).

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https://doi.org/10.1016/j.neuropsychologia.2020.107468
Received 6 December 2019; Received in revised form 26 March 2020; Accepted 12 April 2020
Available online 17 April 2020
0028-3932/

One possible account for these inconsistent results may be that most studies are conducted on young adults, who are at the peak of their cognitive functioning. Thus, for young adults, additional resources are unlikely to enhance functioning. Older adults, in contrast, may benefit from the availability of additional resources because these resources may offset age-related cognitive decline. For example, working memory is known to decline with increasing age (e.g, Bopp and Verhaeghen, 2005; Park et al., 2002); therefore, additional resources may help maintain working memory performance in older adults. Age-related working memory declines have also been correlated with changes in brain activity, with some studies reporting decreased activity in older compared to young adults (Nyberg et al., 2009; Podell et al., 2012), which is thought to reflect less efficient cognitive functioning in older adults. Conversely, other studies have shown increased frontal region activity during a working memory task in older compared to young adults (Gutchess et al., 2005; Payer et al., 2006; Schneider-Garces et al., 2010), reflecting recruitment of additional resources to maintain performance.

Many studies have shown that older adults have decreased activity in parietal regions and increased activity in frontal regions compared to young adults during a variety of cognitive tasks. These differing brain activity patterns between young and older adults are consistent with the posterior to anterior shift in aging model (PASA) (for a review, see Davis et al., 2007). This model holds that in order to compensate for deficits in parietal brain regions, older adults may recruit additional frontal regions during a variety of cognitive tasks, including tasks measuring attention (Cabeza et al., 2004), episodic memory encoding (Anderson et al., 2000; Dennis et al., 2007), and working memory (Rypma & D'Esposito, 2000). However, not all studies have supported PASA, with some studies reporting age-related decreases in frontal activity during encoding (Stebbins et al., 2002) and even increased parietal region activity during a working memory task (Cabeza et al., 2004). Researchers have observed that older adults may also show increased activation during easy tasks relative to young adults. This increased activity during easy tasks is termed over-recruitment. As task difficulty increases, a plateau in brain activity occurs because fewer resources are available. If task difficulty continues to increase after the plateau in brain activity, a decrease in activation is often observed in conjunction with decreases in behavioral performance. This finding is captured in the Compensation-Related Utilization of Neural Circuits Hypothesis model(CRUNCH; Reuter-Lorenz and Lustig, 2005).

Given that some studies have shown strengthened executive control processes in bilinguals (Bialystok and Craik, 2010), some researchers have argued that bilingualism may be protective against age-related declines in executive control (Bialystok et al., 2005). It should, however, be noted that several studies have indicated no cognitive advantage in older adult bilinguals compared to monolinguals in cognitive domains such as inhibition or monitoring skills (e.g., Antón et al., 2016; Kousaie and Phillips, 2012a). It thus remains unclear whether bilingualism offers a cognitive advantage to either young or older adults.

Most studies to date have relied on behavioral measures, which may not be sensitive enough to identify group differences. Electrophysiology may offer additional insight into the effects of bilingualism on cognitive processing and neural mechanisms. Electrophysiological studies have found effects of bilingualism in cognitive monitoring, task switching, and working memory tasks (Barac et al., 2016; Kousaie and Phillips, 2012b; Zunini, Morrison, Kousaie and Taler, 2019; Moreno et al., 2014; Morrison et al., 2019; Morrison et al., 2018). In many of these studies, behavioral differences were not observed (Kousaie and Phillips, 2012b; Morrison et al., 2018, 2019).

The goal of this study was to examine the effect of bilingualism on working memory performance in young and older adults. We had young and older monolinguals and bilinguals complete a delayed match-to-sample (DMS) task, while their electroencephalography (EEG), accuracy, and reaction time were recorded. We then extracted event-related potentials (ERPs), that is, neural responses to specific cognitive events. The ERP components of interest here are the P2, N2, and P3b.

The P2 is a positive-going component that normally occurs 150–300 ms after stimulus presentation (Luck, 2014) and is associated with attentional allocation in working memory (Finnigan, O'Connell, Cummins, Broughton and Robertson, 2011; Lijffijt et al., 2009). The negative-going N2 occurs 200–350 ms post-stimulus presentation (Folstein and Van Petten, 2008) and reflects the ability to discriminate an incongruity between a current stimulus and the representation of a stimulus held in memory (Bennys et al., 2007; Folstein and Van Petten, 2008; Patel and Azzam, 2005) and the amount of effort needed to complete the task (Fitzgerald and Picton, 1983; Jodo and Kayama, 1992). The final component of interest is the P3b, which occurs 300–600 ms post-stimulus and indexes many cognitive processes such as cognitive control, attention, and working memory processing (Mertens and Polich, 1997; Polich, 2007).

In a previous study examining ERP differences between young adult monolinguals and bilinguals using a DMS task, we found that bilinguals exhibited larger P3b and smaller N2 amplitudes, although behavioral differences were not observed (Morrison et al., 2019). The current study compares the same sample of young adult monolingual and bilinguals to a sample of monolingual and bilingual older adults. Based on our past findings, we expect that bilinguals will exhibit larger P3b amplitudes than monolinguals, smaller N2 amplitudes, and similar P2 amplitudes. ERP differences are expected to be more pronounced in older than young adults.

2. Methods

One hundred and twenty participants were recruited for this study. Young adults were recruited through word-of-mouth at the University of Ottawa, and older adults were recruited through word-of-mouth and flyers at community centers. Of the 120 recruited, the data of nine participants were excluded. The EEG of five participants were noisy, resulting in the rejection of more than 25% of data. Four participants misunderstood the instructions and responded with the inappropriate response keys. The remaining 116 were included in the study: 26 young adult English monolinguals (16 females), 28 young adult bilinguals (20 females); 31 older adult English monolinguals (22 females), and 31 older adult bilinguals (21 females). Bilingual participants had high self-reported proficiency in both English and French. Demographic information and neuropsychological test scores are provided in Table 1.

Participants completed a health questionnaire to screen for and exclude participants with neurological and psychiatric conditions, medication usage that can influence the central nervous system or cognitive functioning, and to ensure they had not suffered any major head injuries. Participants also completed a self-rated language proficiency for English and French to determine fluency in speaking, reading, listening, and writing. Additionally, bilinguals completed a language questionnaire to assess the frequency of use for both English and French. Potential monolinguals who rated their ability in French above a 2 ("very little ability") in any modality were excluded. Potential participants who rated knowledge of another language (other than French or English) above a 2 were also excluded. Monolingual participants all had a basic understanding of some French common terms, gained through their education in elementary school as part of the Ontario School Board Curriculum. However, these participants never became fluent and have low exposure to French (language usage and proficency scores are presnted in Table 2). The study received ethical approval from the ethics board at Bruyère Research Institute and the University of Ottawa; participants provided informed written consent before starting the study and were compensated $10 an hour.

3. Procedure

Participants completed two testing sessions, each lasting

Table 1
Group mean (SD) for demographic data and neuropsychological measures.

	Young Monolingual	Young Bilingual	Older Monolingual	Older Bilingual	Age Effect[a]	Language Effect[b]	Age* Language Effect[c]
N (females)rowhead	26 (16 females)	28 (20 females)	28 (19 females)	29 (19 females)	–	–	–
Age	20.16 (2.21)	20.54 (2.10)	73.46 (4.68)	72.27 (4.50)	–	.003	.01
Education	14.96 (1.77)	15.25 (1.76)	15.29 (2.75)	16.62 (2.70)	.038	.04	.01
MoCA	28.35 (1.40)	28.15 (1.67)	27.46 (1.55)	27.24 (1.43)	.079	.002	.001
Digit Span Forward	10.96 (2.19)	11.29 (2.66)	10.92 (2.09)	10.31 (1.98)	.012	.001	.01
Digit Span Backward	6.84 (1.93)	7.86 (2.52)	7.57 (2.34)	7.27 (1.85)	.002	.001	.008
Letter # Sequencing	11.16 (2.08)	12.89 (2.87)	10.50 (2.06)	9.41 (1.81)	**.18****	.002	**.08****
WCST	4.24 (1.16)	4.57 (0.92)	3.75 (1.23)	3.59 (1.29)	**.12****	.000	.007
Stroop1	109.68 (13.39)	109.57 (17.79)	99.89 (18.13)	92.07 (16.01)	**.15****	.02	.008
Stroop2	81.00 (10.90)	79.00 (11.59)	68.07 (14.12)	59.28 (11.84)	**.33****	**.053***	.02
Stroop3	50.32 (11.66)	53.75 (11.57)	36.71 (8.76)	36.51 (5.86)	**.41****	.60	.004
Digit Symbol-Written	64.80 (11.91)	65.92 (10.22)	43.25 (6.77)	43.86 (8.13)	**.58****	.68	.000
Digit Symbol-Oral	70.15 (10.65)	76.00 (113.77)	50.18 (8.07)	49.93 (7.09)	**.60****	.29	.013
BNT-English (/60)	53.04 (3.34)	50.18 (7.61)	52.36 (4.28)	49.48 (5.17)	.006	**.073****	.000
FAS Fluency - English	39.62 (9.08)	41.79 (13.94)	42.04 (11.18)	39.86 (10.28)	.000	.000	.006
Animals - English	24.00 (5.34)	22.32 (6.09)	19.64 (5.12)	17.90 (3.59)	**.13****	.02	.000
FAS Fluency - French	–	28.24 (10.03)	–	35.48 (8.45)	**.14****	–	–
Animals - French	–	18.11 (6.85)	–	16.86 (5.08)	.01	–	–
BNT - French (/60)	–	36.82 (10.02)	–	42.23 (6.9)	**.17****	–	–

Notes: Main effects and interactions show the partial eta squared, *$p < .05$, **$p \leq .005$ BNT = Boston Naming Test, WCST = Wisconsin Card Sorting Test (categories completed). Stroop1 = read name of colors, Stroop2 = name the color of Xs, Stroop3 = read 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.

[a] Young adults scored higher on letter-number sequencing, WCST, Stroop1-3, animal fluency, and digit symbol written and oral than older adults.

[b] Bilinguals performed worse than monolinguals on the Stroop 2 and English BNT. [c]Bilingual young adults performed higher than all other groups.

Table 2
Relative use of language and self-reported proficiency ratings: group mean (SD).

	Young Monolinguals	Young Bilinguals	Older Monolinguals	Older Bilinguals	Age Effect[a]	Language Effect[b]	Age* Language Effect[c]
French Age of Acquisition	6.06 (1.56)	4.57 (2.70)	15.1 (11.44)	6.75 (5.80)	.08*	–	–
French Age of Fluency	–	10.32 (3.30)	–	11.28 (7.40)	.02	–	–
English Proficiency Rating							
Listening	4.92 (0.27)	4.93 (0.26)	4.83 (0.48)	4.75 (0.44)	**.03***	.002	.002
Reading	5 (0)	4.93 (0.26)	4.96 (0.19)	4.86 (0.35)	.01	.024	.001
Speaking	5 (0)	4.93 (0.26)	4.89 (0.31)	4.67 (0.50)	**.07***	**.05***	.012
Writing	4.96 (0.20)	4.93 (0.26)	4.82 (0.61)	4.56 (0.59)	**.07***	.03	.013
French Proficiency Rating							
Listening	1.70 (0.46)	4.54 (0.51)	1.42 (0.70)	4.79 (0.41)	.02	**.89****	**.10***
Reading	1.70 (0.55)	4.50 (0.51)	1.62 (0.74)	4.72 (0.53)	.000	**.88****	**.08***
Speaking	1.67 (0.48)	4.39 (0.50)	1.42 (0.57)	4.76 (0.51)	.003	**.89****	**.14****
Writing	1.54 (0.51)	3.96 (0.74)	1.42 (0.70)	4.55 (0.51)	**.05***	**.83****	**.16****
French use at home							
Listening	–	30.77% (39.56)	–	53.26% (37.16)	**.08***	–	–
Reading	–	36.53% (36.21)	–	50.00% (33.71)	.04	–	–
Speaking	–	26.92% (27.31)	–	35.86% (22.39)	.03	–	–
Writing	–	25.96% (27.82)	–	43.47% (29.40)	**.09***	–	–
French use at school/work:							
Listening	–	37.50% (24.78)	–	44.56% (26.55)	.03	–	–
Reading	–	41.34% (23.39)	–	43.47% (24.09)	.002	–	–
Speaking	–	32.69% (22.10)	–	40.22% (24.70)	.03	–	–
Writing	–	30.77% (21.57)	–	43.48% (28.42)	.06	–	–

Notes: Main effects and interactions show the partial eta squared, *$p < .05$, **$p \leq .005$ 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 ability. 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.

[a] Young adults reported an earlier age of acquisition and higher self-report ratings on their English listening, speaking, and writing than older adults. Older adults had higher self-reported French writing abilities than young adults.

[b] Monolinguals reported their English speaking as higher than bilinguals. Bilinguals reported higher French listening, reading, speaking, and writing than monolinguals.

[c] Based on self-report, bilingual older adults had higher French listening, reading, and writing abilities than bilingual young adults.

approximately 1.5 h. The first session comprised an extensive neuropsychological test battery to assess language proficiency and cognitive functioning. The test battery included the Montreal Cognitive Assessment (MOCA; Nasreddine et al., 2005), the letter-number sequencing task, forward and backward digit span, written and verbal Digit Symbol Substitution subtests of the Wechsler Adult Intelligence Scale-III (WAIS-III; Wechsler, 1997), the Stroop task (Stroop, 1935), the Wisconsin Card Sorting Test (Grant and Berg, 1948), verbal fluency (controlled oral word association test: FAS (Borkowski et al., 1967) and animal fluency) and the Boston Naming Test (BNT; Kaplan et al., 1983). Bilingual participants completed the fluency tasks and BNT in both English and French. During the second session, participants completed the DMS task while their EEG, accuracy, and reaction times were recorded.

3.1. Delayed match-to-sample task

The DMS task includes three conditions (low, medium, and high working memory load). For each condition, the participant first saw a fixation cross for 1000 ms, followed by a display of 1, 3, or 5 numbers (varying in duration between conditions; see below), a retention period of 500 ms, and then a probe stimulus (single number) for 1500 ms. When the probe was presented, participants had to indicate whether it matched one of the numbers initially shown. Trial duration increased with set size. For low memory load, one number was presented for 1200 ms, for medium load, three numbers were presented for 3600 ms, and for high load, five numbers were presented for 6000 ms (see Fig. 1). For all conditions, participants responded yes by pressing the "A" key and no by pressing the "L" key on the keyboard. Each condition included 120 trials, equally balanced between yes and no responses.

3.2. EEG data recording and analysis

Thirty-two active silver-silver electrodes attached to an electrode cap (Brain Products, GmbH, Munich, Germany) placed according to the international 10–20 system were used to record EEG activity. All impedances were kept below 20 kΩ and the EEG was digitized at a rate of 500 Hz with a time constant of 2 s. The FCz location was used as the reference during recording, but offline a new reference for all channels was generated using an average of both mastoids (M1 and M2).

The physiological signals were reconstructed using Brain Products' Analyzer software (Brain Products, GmbH, Munich, Germany). The EEG was down-sampled to 250 Hz, then digitally filtered using a low pass filter of 30 Hz and a high pass filter of 0.1 Hz. The EEG was visually inspected for channels that contained high levels of noise. These channels were replaced by interpolating the data of the surrounding electrode sites (Perrin et al., 1989). Due to low levels of noise, interpolation was only completed in two participants on temporal electrode sites that were not of interest to this study. Vertical eye movements and blinks were measured by placing an electrode on the infraorbital ridge of the left eye and calculated by subtracting the infraorbital electrode from the FP1 electrode. Horizontal eye movement was computed by subtracting F7–F8 electrode activity. Independent Components Analysis was used to identify and remove eye movements and blink artifacts that were statistically independent of the EEG activity (Makeig et al., 1996). These vertical and horizontal eye movements were then partialled out from the EEG activity. The EEG was reconstructed into 1200 ms epochs, which included a 200 ms pre-stimulus baseline period. Trials containing values greater than ±100 μV relative to the baseline on the EEG channels were excluded from further analysis and rejected from the averaging. Only correct trials were included in averages.

The stimuli in the working memory task elicited a series of negative- and positive-going ERP deflections. To determine P2 amplitude, the mean amplitude of the all data points with ±20 ms of the peak in the grand averaged waveform was used. The mean amplitude of the N2 and P3b were generated by using ±50 ms of the peak in the grand averaged waveform. A separate grand average was generated for the young and older adults. Consistent with previous research, the time of the peak for all components differed between young and older adults (Daffner et al., 2011; Gajewski and Falkenstein, 2014). For this reason, the time interval in which mean amplitude was calculated varied between age groups. For young adults, the following time windows were used: P2, 170–210 ms; N2, 220–320 ms; and P3b, 290–390 ms. The time intervals for older adults in the P2 and N2 were 210–250 ms and 270–370 ms, respectively. The peak of the P3b was delayed with increasing set size in older adults. For that reason, different time windows were used for each set size (low memory load, 370–470 ms; medium memory load, 420–520 ms; high memory load, 440–540 ms). Lastly, the late slow wave was analyzed in two different time windows, 600–700 ms and 800–900 ms. Regions of interest were averaged using the following sites: frontal (F3, Fz, F4), fronto-central (FC1, FCz, FC2), central (C3, Cz, C4), and parietal (P3, Pz, P4).

Three 4-way ANOVAs were run for the P2, N2, and P3b with the within-subjects factor of Condition (low, medium, high load) and site (frontal, fronto-central, central) the between-subjects factors of Group (Monolingual and Bilingual) and Age (Young and Older). In addition, a 4-way ANOVA was run for the P3b using the same within-subjects and between-subjects factors at the parietal ROI. Two additional ANOVAs were completed for the slow wave with the within-subject factor of Condition (low, medium, high load) and site (frontal or parietal) and Time (600–700, 800–900) and the between-subjects factors of Group (Monolingual and Bilingual).

4. Statistical analysis and results

4.1. Neuropsychological data

All neuropsychological results were analyzed in a MANOVA with language and age as fixed factors and the neuropsychological test scores as the dependent variable (see Table 1 for scores).

4.2. DMS task performance

Behavioral performance means for the language and age are presented in Table 3. Trials with reaction times (RTs) exceeding ±2.5 standard deviations from the mean within each group and condition were excluded as outliers (outliers comprised less than 1% of all trials). Accuracy and reaction time were analyzed with 3-way mixed ANOVAs with the within-subject factor of Condition (low, medium, and high

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

Measures for DMS Mean (Standard Deviation)	Young Monolinguals	Young Bilinguals	Older Monolinguals	Older Bilinguals
1 number				
RT (ms)	621.12 (101.72)	587.45 (120.47)	727.65 (106.66)	687.60 (111.00)[a]
Accuracy (%)	94.36 (2.02)	93.91 (3.34)	95.56 (3.32)	96.36 (1.17)
Omissions (#)	2.72 (0.89)	3.39 (1.26)	2.46 (1.07)	2.66 (0.86)[b]
Commissions (#)	1.00 (1.22)	1.14 (1.33)	1.25 (2.22)	0.62 (0.78)
3 numbers				
RT (ms)	742.32 (120.47)	717.19 (144.53)	844.59 (89.80)	847.77 (120.04)[a]
Accuracy (%)	94.31 (4.10)	94.68 (3.29)	95.99 (3.19)	95.80 (3.41)
Omissions (#)	0.52 (0.71)	0.64 (0.73)	0.46 (0.92)	0.21 (0.41)
Commissions (#)	2.04 (2.94)	1.79 (1.93)	1.61 (2.50)	1.03 (1.27)
5 numbers				
RT (ms)	796.18 (124.69)	775.37 (136.37)	920.74 (96.25)	954.63 (128.98)[a]
Accuracy (%)	92.67 (5.53)	90.75 (8.35)	92.61 (7.46)	90.57 (7.17)
Omissions (#)	1.16 (1.43)	1.21 (1.47)	0.75 (1.04)	0.45 (1.02)
Commissions (#)	3.32 (3.23)	3.39 (3.90)	2.00 (3.08)	1.76 (1.55)[c]

Notes: A total of 26 monolinguals took part in the study; however, one monolingual's behavioral data was lost due to computer error.
[a] Young adults were overall faster than older adults (main effect; $p < .001$), which was the case for all conditions (Age* Condition interaction, $p < .001$).
[b] Older adults had overall fewer omission (main effect; $p = .002$).
[c] commission errors than young adults ($p = .025$).

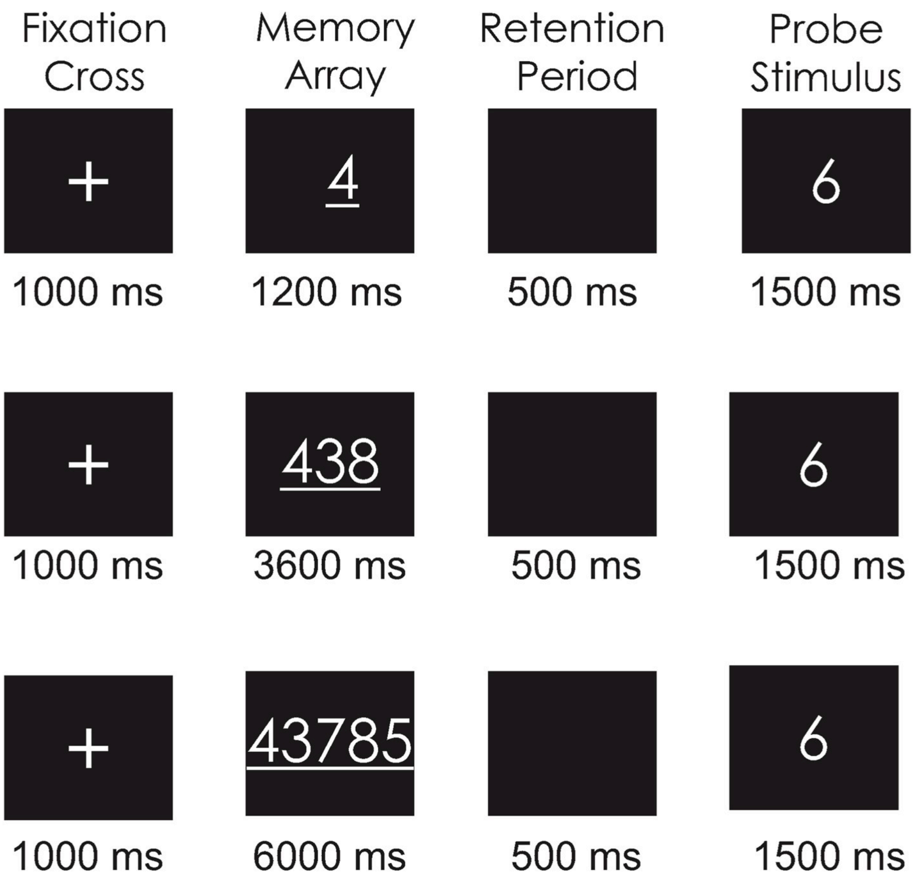

Fig. 1. An example of the stimuli used for each condition and timing of stimulus presentation for the delayed matching-to-sample task. In all examples shown above participants would respond "no" by pressing the "L" key to state that the probe stimulus does not match the memory array.

memory load) and between-subjects factors of Language (Monolingual and Bilingual) and Age (Young and Old).

Working memory load had a significant effect on performance. Accuracy was lower in high (92%) than medium (95% $p < .001$) and low load (95%, $p < .001$; main effect of Task Difficulty, $F\,(2{,}212) = 36.65$, $p < .001$, $n^2_p = .26$). There were no main effects or interactions for accuracy involving age or language.

Working memory load also had a significant effect on reaction time. Reaction time increased as working memory load increased (low load: 655 ms, medium load: 786 ms, high load: 859 ms), with all conditions

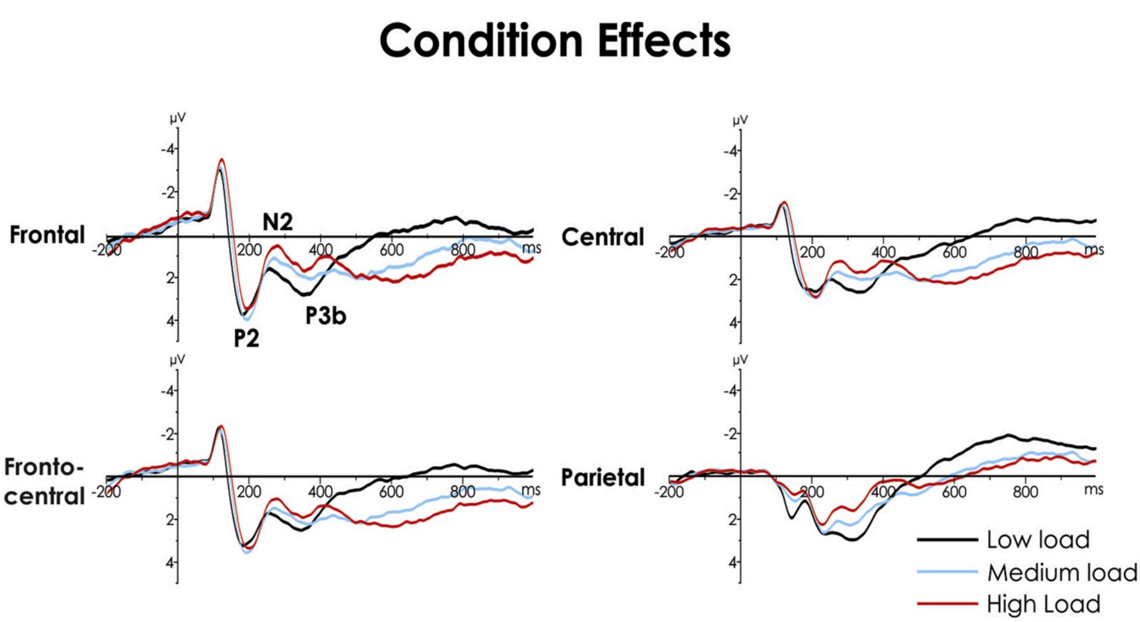

Fig. 2. ERP waveforms collapsed across age and language to show the main effects of condition on all components at each site of interest. Averages at frontal (F3, Fz, F4), fronto-central (FC1, FCz, FC2), central (C3, Cz, C4), and parietal (P3, Pz, P4) regions are shown. Negative is plotted up.

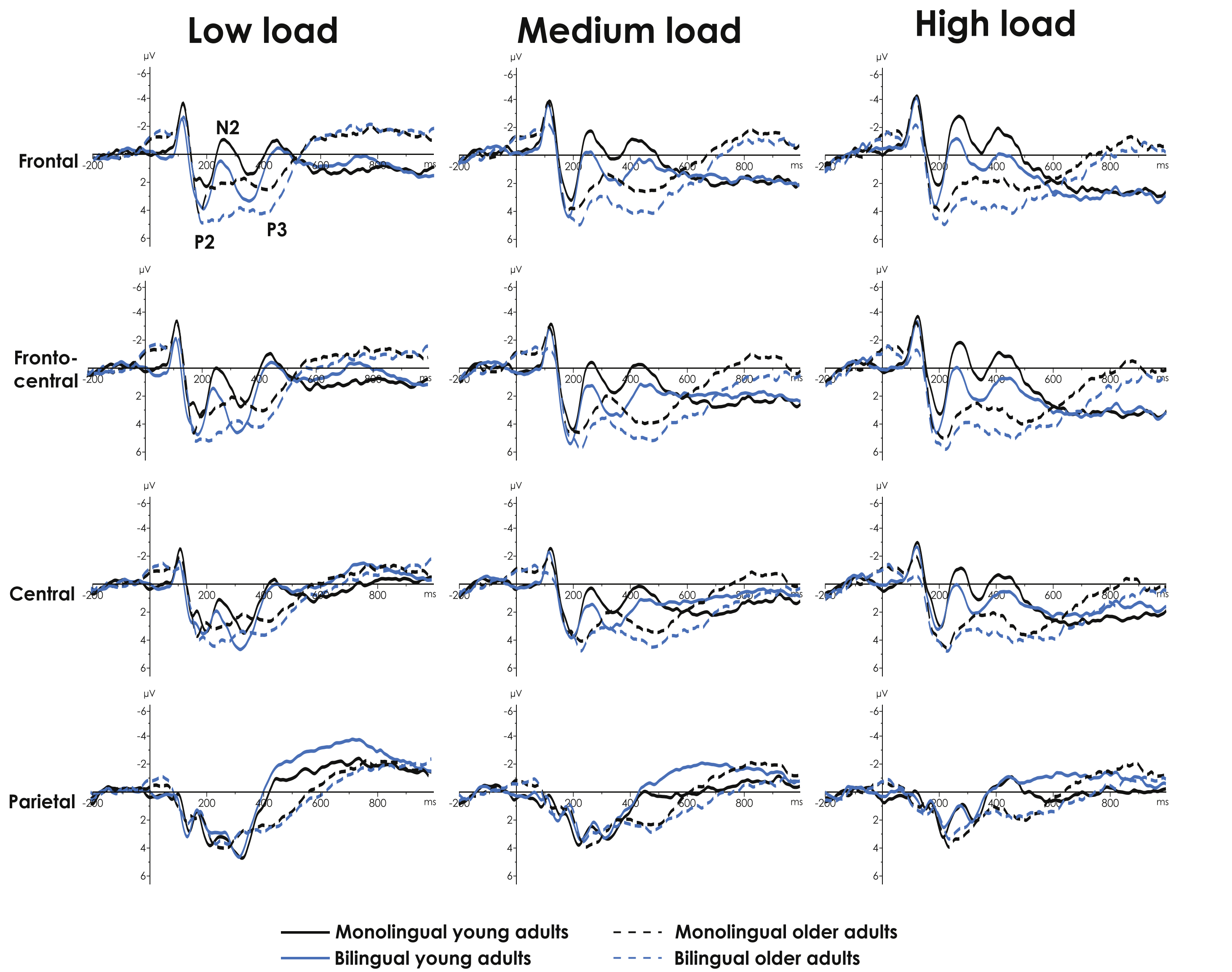

Fig. 3. ERP waveforms displaying young and older monolingual and bilingual adults across conditions at each site of interest. Averages at frontal (F3, Fz, F4), fronto-central (FC1, FCz, Fc2), central (C3, Cz, C4), and parietal (P3, Pz, P4) regions are shown. Negative is plotted up.

significantly differing, $p < .001$ (main effect of Task Difficulty, F (2,212) = 464.57, $p < .001$, $n^2_p = .81$). Compared to older adults, young adults had overall faster reaction times (main effect of Age, F (1,106) = 34.80, $p < .001$, $n^2_p = .25$). There were no significant main effects or group interactions involving language.

4.3. ERP results

Fig. 2 illustrates the different ERP deflections elicited by the target probe stimulus across conditions. A positivity, P2, occurring at about 200 ms was maximum over anterior, frontal and fronto-central sites. It was followed by a widespread negative-going N2 occurring at about 280 ms. A later, larger positivity, the P3b, also had a widespread scalp distribution. Its morphology was that of a longer-lasting slow wave occurring from 400 to 600 ms, rather than as a distinct peak (see Fig. 3).

4.3.1. P2

In frontal, fronto-central, and central ROIs, a significantly larger P2 amplitude was elicited in the medium load compared to the high and low load conditions (main effect of Task Difficulty, F (2,214) = 4.79, p = .014, $n^2_p = .04$). Bilinguals displayed a larger P2 amplitude than monolinguals (main effect of Language, F (1,107) = 4.06, $p = .046$, n^2_p = .04). The main effect of age revealed that young and older adults did not significantly differ ($p > .05$). However, young adults did exhibit smaller amplitudes than older adults during only the high load condition (interaction between Task Difficulty and Age, F (2,214) = 4.55, $p = .017$, $n^2_p = .04$). This interaction also revealed that young adults had smaller amplitudes in the high load compared to the medium load condition. On the other hand, older adults' P2 amplitude was not influenced by task difficulty. No significant interactions involving language were observed.

4.3.2. N2

In frontal, fronto-central, and central ROIs, N2 amplitude increased as working memory load increased (main effect of Task Difficulty, F (2,214) = 1.89, $p < .001$, $n^2_p = .09$). Monolinguals had larger N2 amplitudes than bilinguals regardless of working memory load (main effect of Language, F (1,107) = 9.00, $p = .003$, $n^2_p = .08$). Young adults also exhibited larger N2 amplitudes than older adults (main effect of Age, F (1,107) = 22.00, $p < .001$, $n^2_p = .17$). A significant Age by Condition interaction was also apparent, F (2,214) = 9.85, $p < .001$, $n^2_p = .08$. In young adults, the amplitude of N2 became larger as working memory load increased. On the other hand, the amplitude of N2 did not increase

Table 4
Summary of ERP results.

ERP component/ description	Condition Effects	Age Effects	Language Effects
P2 Anterior positivity occurring 150–300 ms post-stimulus; related to attention and working memory; larger amplitude reflects greater attentional allocation and working memory performance	Medium > high and low YA medium > high OA low = medium = high	YA < OA in high only	Monolinguals < bilinguals
N2 Anterior negativity occurring 200–350 post-stimulus; related to effort during task completion; larger amplitude reflects greater effort for task completion	Low < medium < high YA low < medium < high OA low = medium = high	YA > OA	Monolinguals > bilinguals
P3b Posterior positivity occurring 300–600 ms post-stimulus; related to available resources and working memory; larger amplitude reflects additional resources available for task completion	**Frontal:** Low and medium > high YA low > medium > high OA low = medium = high **Parietal:** Low > medium > high	**Frontal:** YA < OA **Parietal:** YA > OA in low only	**Frontal:** Monolinguals < bilinguals **Parietal:** n.s.
Late Slow Wave Anterior negativity and posterior positivity occurring 600+ post-stimulus; related to mental events in task processing and effort; larger amplitude reflects the exertion of more effort during discrimination of stimulus and initiating a response	**Frontal:** More + ive with increasing difficulty **Parietal:** More + ive with increasing difficulty	**Frontal:** OA more -ive then YA **Parietal:** OA more + ive then YA in low only	**Frontal:** n.s. **Parietal:** n.s.

Notes: YA = young adult, OA = older adult, n.s. = no significant differences.

as a function of working memory load for older adults. No significant interactions involving language were observed.

4.3.3. P3b

At frontal, fronto-central, and central sites, P3b amplitude was affected by working memory load. The P3b was significantly smaller in the high load condition than in the medium and low load conditions (main effect of Task Difficulty, F (2,214) = 5.82, p = .006, $n^2{}_p$ = .05). Smaller P3b amplitudes were displayed by monolinguals compared to bilinguals (main effect of Language, F (1,107) = 6.32, p = .013, $n^2{}_p$ = .06). Young adults also had smaller P3b amplitudes than older adults (main effect of Age, F (1,107) = 11.00, p = .001, $n^2{}_p$ = .09); this effect was driven by older adults having larger amplitudes than young adults during the medium and high load conditions (interaction between Task Difficulty and Age, F (2,214), $p < .001$, $n^2{}_p = .12$). This interaction also revealed that young adults' P3b amplitude varied as an effect of working memory load (smaller with increasing memory load) while for older adults, P3b amplitude was not influenced by memory load.

At the parietal ROI, P3b amplitude significantly decreased as working memory load increased (main effect of Task Difficulty, F (2, 214) = 31.78, $p < .001$, $n^2{}_p = .23$). There were no significant overall differences in parietal P3b amplitude due to language or age (F < 1). However, P3b amplitude was significantly larger in young adults compared to older adults, but only in the low load condition (interaction between Task Difficulty and Age, F (2, 214) = 7.69, p = .001, $n^2{}_p$ = .07).

4.3.4. Late slow wave

The frontal region analysis revealed that with increased task difficulty the slow wave negativity became more positive (main effect of Task Difficulty, F (2,212) = 41.31, $p < .001$, $n^2{}_p = .28$). No main effect of language was observed. Older adults had more negative amplitudes than young adults (main effect of Age, F (1,106) = 25.00, $p < .001$, $n^2{}_p = .19$). No additional interactions were significant.

The parietal region analysis also revealed that the slow wave became more positive with increasing task difficulty (main effect of Task Difficulty, F (2,212) = 39.77, $p < .001$, $n^2{}_p = .27$). There were no main effects involving age or language. Young adults had more negative amplitudes than older adults in the low working memory load condition (interaction between Condition and Age, F (2,212) = 5.16, p = .011, $n^2{}_p$ = .05). No additional interactions were significant.

A summary of ERP results are presented in Table 4. To summarize, differences between young and older adults were found in many of the ERP components of interest. First, young adults displayed smaller P2 amplitudes than older adults in the frontal, fronto-central, and central regions in the high load condition. Second, N2 amplitude was larger in young compared to older adults. Third, young adults displayed a smaller amplitude P3b than older adults at frontal, fronto-central, and central sites during the medium and high load conditions. At parietal regions a larger P3b amplitude in young adults was only present in the low load condition. Fourth, older adults displayed a more negative late slow wave activity than young adults in anterior regions. Fifth, both the N2 and P3b were unaffected by task difficulty in older adults, whereas in young adults the amplitudes changed as a function of task difficulty increased.

Effects of bilingualism were observed in the P2, N2, and P3b. At frontal, fronto-central, and central sites monolinguals exhibited larger N2 amplitudes and smaller P2 and P3b amplitudes than bilinguals. There were no language differences in parietal P3b analysis. No interactions were observed between Age and Language.

5. Discussion

The present study was designed to examine how fluency in a second language was associated with performance and processing during a working memory task. Previous studies have generally indicated that bilinguals manifest superior performance on a number of cognitive tasks. These studies have however been carried out almost exclusively with young adult samples using behavioral measures. The presentstudy included an older adult sample of bilinguals and monolinguals. ERPs were recorded while participants completed a delayed matching-to-sample (DMS) task.

5.1. Behavioral effects

Behavioral performance was significantly affected by increasing working memory load from one to five items. Reaction time significantly increased with increasing load. Accuracy was high in all conditions, but was significantly lower in the low than the medium and high load conditions. Bilingualism was not associated with differences in performance. Thus, neither accuracy nor reaction time significantly differed between monolinguals and bilinguals, and age did not interact with language. Reaction time was significantly longer in older than young adults, while accuracy did not significantly differ between older and young groups. While accuracy of performance was similar across groups, ERPs were notably different.

5.2. P2

The P2 peaked at approximately 200 ms and was maximal over frontal and frontocentral regions. At these regions, the P2 was significantly larger for bilinguals than for monolinguals, regardless of age.

There is evidence that working memory capacity is associated with the ability to control attention (Unsworth and Spillers, 2010; Kane et al., 2001), with larger P2s suggested to reflect greater attentional allocation, resulting in better working memory performance (Finnigan et al., 2011; Li et al., 2016). Therefore, one interpretation of the increased P2 in bilinguals is increased attention to the test stimulus. However, this is difficult to reconcile with similar performance on the task between monolinguals and bilinguals. In addition, the P2 was larger in older than young adults, particularly in the high working memory load condition. Similar to language differences, the P2 age-group effect may be related to attention, but in the case of age it may reflect compensatory mechanisms. Because a larger P2 in older adults was only found in the high working memory load condition, this finding may reflect older adults' need to exert more attention to the task at hand when it becomes more difficult. This compensatory processing, perhaps reflected in the P2, may explain how older adults performed as well as young adults on the task.

5.3. N2

The N2 was maximal at anterior sites and occurred at approximately 280 ms post-stimulus presentation. N2 amplitude increased with higher working memory load. The N2 has been suggested to reflect the requirement for increased effort during difficult tasks (Pinal et al., 2014). In the present study, monolinguals exhibited a larger N2 than bilinguals, consistent with a need for greater effort in the monolinguals to maintain performance similar to that of the bilinguals.

However, such an interpretation is difficult to make when considering the older adult data, because older adults also exhibited a smaller N2 than young adults. An interpretation suggesting that the memory task was easier and required less effort for older adults seems to be counterintuitive. The increased N2 amplitude in young adults with increasing task difficulty is consistent with the need for greater effort. It is difficult to explain why a similar increase in the N2 with increasing difficulty was not observed in the older group. It is possible that the older adults performed the task with the same effort regardless of the number of items in the memory set, but such an interpretation does not coincide with reaction time. Reaction times were much slower for the older group, suggesting prolonged and more effortful controlled processing compared to young adults. Therefore, the reduced N2 in the older group is likely a result of the overlapping long-lasting positivity. This overlapping positivity is discussed further with the P3b results.

5.4. P3b

The P3b component occurred between 290 and 600 ms post-stimulus presentation. Although often parietally maximal (Polich, 2007), the P3b has also been examined in anterior regions during working memory tasks (e.g., Padgaonkar et al., 2017; Saliasi et al., 2013). In the present study, a large P3b was also evident over anterior regions, with a smaller P3b observed in parietal regions.

At parietal sites, the amplitude of the P3b decreased as working memory load increased. The parietal P3b did not, however, differentiate between monolingual and bilingual groups. There was a difference between young and older adults, but only during the low load condition. As working memory load increased, the young-older P3b differences were no longer apparent. Many studies have reported that the parietal P3b is larger for young than older adults during working memory tasks (McEvoy et al., 2001; Saliasi et al., 2013).

Interpreting the anterior P3b is difficult because both the bilingual and the older adult groups' waveform was quite similar. A larger P3b was observed in bilinguals compared to monolinguals and in older adults relative to young adults. The bilingual group displayed significantly larger P3b amplitudes than monolinguals across all working memory load conditions. This increased amplitude could be explained by the availability of additional resources (Kok, 2001; Polich, 2004) for task completion in bilinguals. This finding is consistent with several studies reporting increased P3b amplitude in bilinguals relative to monolinguals during executive functioning (Barac et al., 2016; Moreno et al., 2014; Sullivan et al., 2014) and working memory tasks (Morrison et al., 2018).

Similarly, the anterior P3b was also larger for older than young adults across the medium and high load conditions. The explanation of additional resources available for task completion that explained the larger P3b in bilinguals does not appear to be appropriate in the case of older adults. This explanation may not be suitable for the older adult data because it is well established that working memory declines with age (Bopp and Verhaeghen, 2005; Brockmole and Logie, 2013; Park et al., 2002). One interpretation of the larger P3b amplitudes in older adults is the use of compensatory mechanisms. Under the supposition that older adults' working memory capacity reached its limits in both the medium and high load conditions, additional resources may have been recruited to maintain performance. Because the older adults could maintain high performance throughout all three working memory loads, we could not determine whether the older adults' ERPs were consistent with the CRUNCH model. Many researchers have suggested that older adults recruit additional frontal regions because of declines in parietal regions seen with increased age (Davis et al., 2007), resulting in increased anterior P3b activity in older relative to young adults (Daffner et al., 2011; Fujiyama et al., 2010; O'Connell et al., 2012; Saliasi et al., 2013; Vallesi, 2011). Therefore, increased P3b amplitudes observed in the older adult group may be explained by additional compensatory efforts allowing the older adult group to maintain similar accuracy to young adults and to prevent errors.

An alternate explanation of the age-group differences may be related to the long-lasting positive shift beginning at the time of the P2. This positivity would explain the apparent reduced anterior N2 but increased P3b in the older adult group. Such extended processing might be reflective of processing associated with cognitive effort. Older adults also exhibited a large anterior slow wave that appeared to overlap with reaction time. This wave has been associated with the mental events involved in processing the task and occurs at approximately the same time as reaction time (for a review see Friedman, 1984). This suggests that older adults may have been exerting more effort during the discrimination process, resulting in longer reaction times.

Applying the compensatory hypothesis to the bilingual group does not seem feasible because research on working memory has suggested that bilinguals either have no advantage or some advantage relative to monolinguals, but no research has suggested a disadvantage (e.g., Grundy and Timmer, 2017; Linck et al., 2014). Even with the apparent additional attention, effort, and/or resources as shown by the differing ERPs, bilinguals did not outperform monolinguals in accuracy or reaction time. Therefore, if the enhanced activity does reflect additional effort or resources in the bilingual group, why is it necessary and why did this difference not result in enhanced performance? It should be noted that increased activity may also reflect inefficient processing: that is, the monolingual group performed as well as the bilingual group while apparently exerting less cognitive effort.

An intriguing finding is the absence of an interaction between language and age. ERP differences that were apparent between young monolingual and bilinguals were also observed in older monolingual and bilinguals. Thus, while the ERP differences in young monolinguals and bilinguals may reflect different processing strategies, these different strategies appear to be invariant and well-maintained until much later in life. The issue of precisely which strategies are being employed requires further research.

5.5. Limitations

There are a few limitations that should be noted in this study. First, the monolinguals' and bilinguals' N1s are not equivalent, and therefore the between-group effects in the following ERP components may be less robust than they appear. While the N1 is associated with early sensory processing, this early component may also be affected by attention in the visual modality (Luck et al., 2000). Future research should examine how task difficulty during a delayed matching-to-sample task influences the N1. Second, without performance differences between groups, the similar ERP waveforms between bilinguals and older adults are difficult to interpret. Future research should replicate this study with more difficult conditions to see how brain activity patterns change due to age and language when working memory capacity is exceeded.

6. Conclusion

Older adults maintained similar accuracy to young adults but exhibited longer reaction times and differences in ERPs. Similarly, bilinguals and monolinguals exhibited similar accuracy and reaction time while showing differences in ERPs. Compared to young adults, older adults displayed larger P2 amplitudes during the high working memory load condition, larger P3b amplitudes during the medium and high working memory load conditions, and larger slow wave amplitudes, in conjunction with increased reaction time. This finding may be interpreted as indicating that older adults recruit more resources as a compensatory mechanism during the more difficult conditions in order to maintain similar performance to their young counterparts. Older adults also exhibited a long-lasting positive potential occurring around the time of the P2, which may account for the smaller N2 and larger P3b amplitude.

The larger P3b exhibited by bilinguals compared to monolinguals might suggest that the former group has more resources available to complete the task. However, because there were no accuracy or reaction time differences between monolinguals and bilinguals, any interpretation of language group differences in ERPs should be undertaken with caution. These findings should be replicated in a more difficult task to determine if the language and age ERP differences translate to performance differences between groups.

Declaration of competing interest

None.

CRediT authorship contribution statement

Cassandra Morrison: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing. **Vanessa Taler:** Conceptualization, Supervision, Funding acquisition, Writing - review & editing.

Acknowledgements

* We thank the participants in this study and Farooq Kamal, Kim Le, and Giovanna Busa for their assistance with data acquisition. This research was funded by a Natural Sciences and Engineering Research Council of Canada (210924-190799) grant to V.T. C.M. received the Mark and Gail Marcogliese Graduate Fellowship for Research from the University of Ottawa Brain and Mind Research Institute.

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