An ERP investigation of the effects of bilingualism on working memory and age-related cognitive decline

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Abstract

Being bilingual appears to afford benefits to cognitive functioning relative to being monolingual. Bilingual advantages have been observed in several areas of cognitive functioning such as task switching, inhibition, and cognitive control. Many studies, however, have been unable to replicate findings of a bilingual advantage. Inconsistencies in these findings may result from methodological differences and limitations within and across studies. Thus, the purpose of the present thesis was to examine if working memory capacity and processing differ between monolinguals and bilinguals using electroencephalography (EEG) to measure event-related potentials (ERPs).

While several studies have observed differences in working memory capacity between monolinguals and bilinguals, these studies have often been limited to behavioral measures. Therefore, it remains unknown if the neural processes differ between monolinguals and bilinguals during working memory. Part 1 of the present thesis examines whether brain activity differs in English monolinguals compared to English-French bilinguals during working memory tasks. Part 1 comprised two paradigms. In Paradigm 1, participants completed an n-back working memory task while EEG was recorded. Results of this study revealed that monolinguals exhibited smaller P3b amplitudes compared to bilinguals. Paradigm 2 employed a delayed matching-to-sample task while EEG was recorded. In both paradigms, monolinguals displayed smaller P3b amplitudes than bilinguals. In Paradigm 2, monolinguals also displayed larger negative slow waves and N2b amplitudes than bilinguals. Both Paradigms found ERP differences in the absence of any behavioral advantage in bilinguals. These findings suggest that bilinguals may have more cognitive resources available in working memory to allocate to task completion than monolinguals.

Part 2 was designed to determine whether bilingual ERP differences translated to a cognitive advantage in healthy older adult English-French bilinguals. Because older adults

experience age-related cognitive decline, any advantages offered by bilingualism may be more pronounced in older adults compared to young adults. As in Part 1, we employed the same two paradigms, (the n-back working memory task; Study 3 and the delayed matching-to-sample task; Study 4). Similar to the results found in young adults, Studies 3 and 4 both revealed that bilinguals exhibited larger P3b amplitudes in the absence of behavioral and neuropsychological differences. Additionally, young and older adults exhibited different patterns of activation during the task, consistent with the compensation utilization of neural circuits hypothesis (CRUNCH).

Part 3 (Study 5) examined whether linguistic distance between the L1 and L2 of bilinguals affects ERPs. Many studies compare participants proficient in Indo-European languages such as English and French. The purpose of Study 5 was to compare the processes associated with working memory processing (using ERPs) in Arabic-English bilinguals to English-French bilinguals. EEG was recorded while participants completed the n-back and delayed matching-to-sample task. In the delayed matching-to-sample task, monolinguals exhibited smaller N2 amplitudes compared to both bilingual groups, and smaller P3b amplitudes compared to English-French bilinguals. In the n-back, English-French bilinguals displayed larger P3b amplitudes than both English monolinguals and Arabic-English bilinguals. P3b amplitude did not differ between Arabic-English bilinguals and monolinguals in either task.

The present work demonstrates that working memory functioning (as indexed by ERPs) may differ between monolinguals and bilinguals in the absence of a behavioral advantage. These findings also suggest that bilingual advantages in working memory are not more pronounced in older adults despite ERP differences. Finally, these results show that ERP differences between Arabic-English bilinguals compared to English monolinguals and English-French bilinguals will vary depending on the component of working memory that the task examines.

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General Introduction

Overview

Over half of the world's population is fluent in more than one language (Costa, 2005). With fluent in two languages becoming more common (Canada Census, 2017, Canada Census, 1996), many researchers are studying whether cognitive advantages are observable in bilinguals and if these advantages can help mitigate age-related cognitive decline.

Previous studies on bilingualism have generated inconsistent findings concerning the effects of bilingualism on various cognitive functions, including cognitive control, task switching, and inhibitory processes. For example, while some researchers have observed that task switching is heightened in bilinguals due to their constant need to switch between languages (e.g., Prior & Macwhinney, 2010), some studies on executive control have shown no such advantages (Paap & Greenberg, 2013). The inconsistencies may be the result of measurement tools lacking sensitivity to observe group processing differences between monolinguals and bilinguals. Behavioral measures provide a single response, in which researchers have to infer the processes involved with the response. However, brain imaging techniques, may be more sensitive than neuropsychological or behavioral measures alone because they provide a direct measure of the cognitive processes that occur before and after the response has been made. Thus, bilingual advantages may be more discernible using imaging techniques which can observe cognitive processing differences. Additionally, the cognitive advantages offered by bilingualism may not be observable in young adults as they are at the peak of their cognitive functioning. Therefore, cognitive benefits may be more pronounced in older adults who experience age-related cognitive declines.

The use of brain imaging techniques such as electroencephalography (EEG) and functional magnetic resonance imaging (fMRI) has increased in the field of psychology due to their ability to examine the neural mechanisms underlying cognitive processes that would otherwise be inferred by a behavioral response. Several studies have shown that the neural processes underlying cognitive functions involved in different tasks may significantly differ even though there are no differences in performance measures (Abutalebi et al., 2012; Gigi, Anderson, Craik, Grady, & Bialystok, 2010b; Kousaie & Phillips, 2012b). These findings show that the inclusion of electrophysiological measures could provide additional insight when investigating bilingualism and the effect it may have on cognitive functions and age-related cognitive declines.

What is Bilingualism?

The term “bilingual” is typically used to describe people who are fluent[1] in two languages. In Canada, the 2016 census showed that 17.9% of the population spoke English and French, up from 11% in 1996 (*Canada Census*, 2017; *Canada Census*, 1996)**.** While this statistic refers solely to English and French bilingualism, over 20% of Canadians speak another language in addition to French and/or English (*Canada Census*, 2017). Worldwide, it is estimated that over half of the population uses two or more languages (Costa, 2005).

The definition of bilingualism has been inconsistent in the literature. While some studies use objective measures, others employ only self-report measures to determine proficiency. For example, Kousaie and Phillips required bilingual participants to have high

[1] Fluency is often used interchangeably with “spoken language competence” or “oral proficiency”. Proficiency is referred to as competency in all aspects of a language (i.e., listening, reading, speaking, and writing) (see Maletina, 2014 for a review). In addition, fluency can also refer to abilities in a non-verbal language such as sign language.

self-reported second language (L2) proficiency, converse in both languages daily, and also show similar performance in English and French on an animacy judgment task (2017). The animacy judgment task is a forced-choice animacy classification paradigm in which participants are presented with 53 animate and 53 inanimate nouns that they must classify as either living (e.g., dog) or nonliving (e.g., chair) (Segalowitz & Frenkiel-Fishman, 2005). Bilingual participants completed the task in both their L1 and L2. L2 proficiency was determined by partialling out performance in their L1 from the performance in their L2. This animacy task allows for researchers to gather more objective measures of L2 proficiency. On the other hand, other studies consider factors such as ability and exposure in L2 to determine if a participant was proficient in two languages. For example, one study asked the participant and their spouse if the participant used both their languages consistently throughout life (Schweizer, Ware, Fischer, Craik, & Bialystok, 2012). In addition, many studies compare monolinguals to bilinguals with several different L2s (e.g., Anderson et al., 2017; Bialystok et al., 2014, 2007; Paap & Greenberg, 2013). These studies rely on self-report to determine L2 proficiency in participants because testing in several languages not possible (Anderson et al., 2017). In studies where several L2s are observed it is very difficult to employ objective measures of L2 proficiency.

Although being bilingual is defined as being proficient in two languages, a person's level of proficiency is influenced by several external factors. These factors include the age of acquisition of the L2, the method of acquisition, and the proficiency in L2 (Hoffman, 2014). These differences in language acquisition can lead to varying degrees of abilities in speaking, listening, reading, and writing both acquired languages. Any two people who identify as bilingual are likely to vary in their proficiency due to the age at which the L2 was acquired and the method of acquisition. Differences in the definitions of bilingualism have led to the development of scales such as, "The Language and Social Background Questionnaire" to measure language experience and social backgrounds (Anderson, Mak, Keyvani Chahi, & Bialystok, 2018). These questionnaires help researchers assess a participant's degree of bilingualism based on exposure and usage of both L1 and L2.

Previous research has provided consistent evidence that language proficiency, usage, and age of acquisition can influence whether group differences between monolinguals and bilinguals are obtained (Luk & Bialystok, 2013; Tao, Marzecová, Taft, Asanowicz, & Wodniecka, 2011). Tao et al. (2011) found that balanced bilinguals showed the largest cognitive advantages over monolinguals. These authors noted that early bilinguals showed enhanced monitoring processes, while late bilinguals showed the greatest conflict resolution advantage. Differences between the early and late bilinguals may be confounded by the late learners showing the most balanced proficiency and usage of both languages. This finding of balanced bilinguals showing the largest advantage has been reported by other researchers, showing that people who spend more actively using both languages display greater advantages in cognitive control (Calvo, Ibáñez, García, & Ellis, 2016; Luk, De Sa, & Bialystok, 2011; Whitford & Titone, 2012). Christoffels et al. (2006) compared working memory among three different groups of bilinguals: professional interpreters, bilingual university students, and highly proficient L2 teachers. Their results showed that professional interpreters outperformed both the university students and L2 teachers on the working memory measures (Christoffels, de Groot, & Kroll, 2006). Taken together, the current research suggests that language usage, proficiency, and age of acquisition can influence whether group differences are observed between monolinguals and bilinguals.

Another limitation in many bilingualism studies relates to the languages being studied. For example, several studies have examined the benefits of bilingualism by including bilinguals who speak several different languages (e.g., Bialystok et al., 2014, 2007). Nevertheless, most studies tend to focus on comparing monolinguals to bilinguals with linguistically similar L1 and L2s (e.g., English monolinguals compared to English-French bilinguals)[2]. However, the languages compared are often similar to each other. Therefore, studying another language such as Arabic, which has a larger linguistic distance (i.e., dissimilarity in word/sentence structure, pronunciation, and grammar (Soliman, 2014)) from English than French may provide more evidence for whether a bilingual cognitive advantage exists. Languages with a larger linguistic distance from English could impose more demands on cognitive processes.

It is thus possible that those who are Arabic-English bilinguals may exhibit enhanced cognitive functioning over those who are English-French bilinguals. There are a few reasons for this possibility: 1) While English and French are both branches of the Indo-European language family, Arabic is part of the Afro-Asiatic family and shares fewer similarities with English than does French, and 2) Arabic has a morphology which is quite different from English and French. Because Arabic is part of a different language family and is less similar to English than French is (i.e., Arabic has a larger linguistic distance from English than French) more resources may be required to not only switch between English and Arabic languages but also maintain both languages compared to English and French. Gollen et al. (2011) suggested that languages which have semantic and lexical overlap (e.g., from the same language family) would place more demands on cognition than linguistically different languages because of the

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[2] It should be noted that throughout the thesis when discussing bilinguals, an L1-L2 naming system will be used. For example, English-French is referring to bilinguals whose L1 is English and L2 is French.

effort required to inhibit interference from similar languages. However, an opposite effect has been observed in the few studies examining linguistic distance (e.g., Bialystok et al., 2005; Wierzbicki, 2014).

Language Families. Languages are organized and grouped based on the ancestral language they are derived from. The branch to which each language is assigned will share the same ancestral language as the other languages on that branch; this grouping is termed a *language family*. Languages that are part of the same family exhibit lexical and grammatical similarities. These groups were made into a family tree model of language which was created in 1861 by August Schleicher (an example is provided in Figure 1; Rowe & Levine, 2015). Figure 1 shows the *parent* (proto) language for Indo-European languages from which each branch is derived. All languages derived from Proto-Indo-European languages are part of the Indo-European tree. As seen in Figure 1, there are several branches of the Indo-European tree, with 445 languages (Eberhard et al., 2020). Although these languages have changed over time, they all share several similarities (Rowe & Levine 2015). Both English and French are Indo-European languages; English is derived from the Germanic branch, whereas French is derived from the Italic branch. Although the Indo-European language is the most-studied language family, it is only one of several language families.

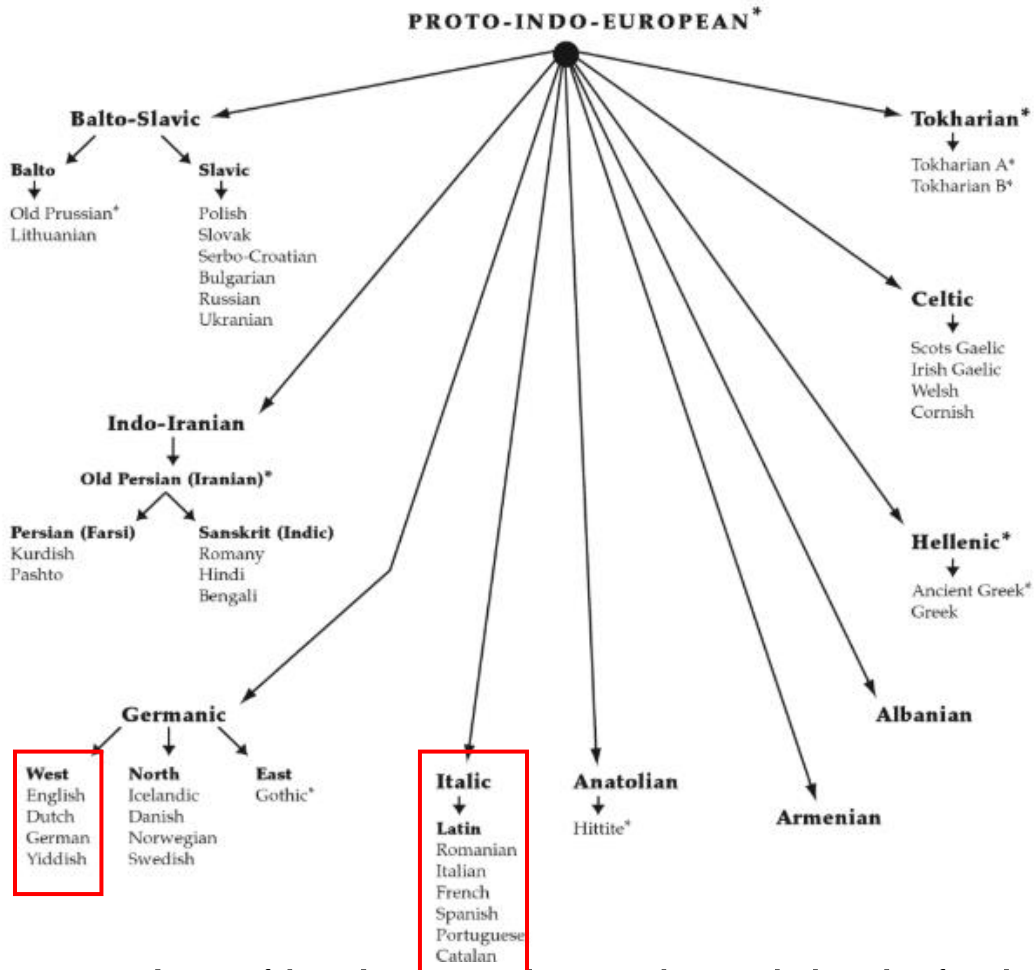

Figure 1. Family tree of the Indo-European language showing the branches for which English and French are derived. Image taken from, "A Concise Introduction to Linguistics" (2015).

Another language family is Afro-Asiatic, which comprises six branches (See Figure 2): Semitic, Chadic, and Cushitic (Frajzyngier, 2018). Afro-Asiatic is the fourth largest language grouping, with over 495 million speakers and 377 different languages (Eberhard et al., 2020). Derived from the Semitic branch, Arabic is the most spoken of the Afro-Asiatic languages. In the 19th and 20th centuries, the "Indo-Semitic hypothesis" (Moller, 1879) suggested that Indo-European and Semitic languages were from the same ancestral origin because of a few similarities in the languages. However, English and Arabic remain on different branches, because the "Indo-Semitic hypothesis" remains unaccepted. It is common for languages of different families and branches to share "false friends" (Al-Wahy, 2009). For example, English and Arabic share "lexical false friends", words that are similar or identical in both languages but have a different meaning in each language (Al-Wahy, 2009).

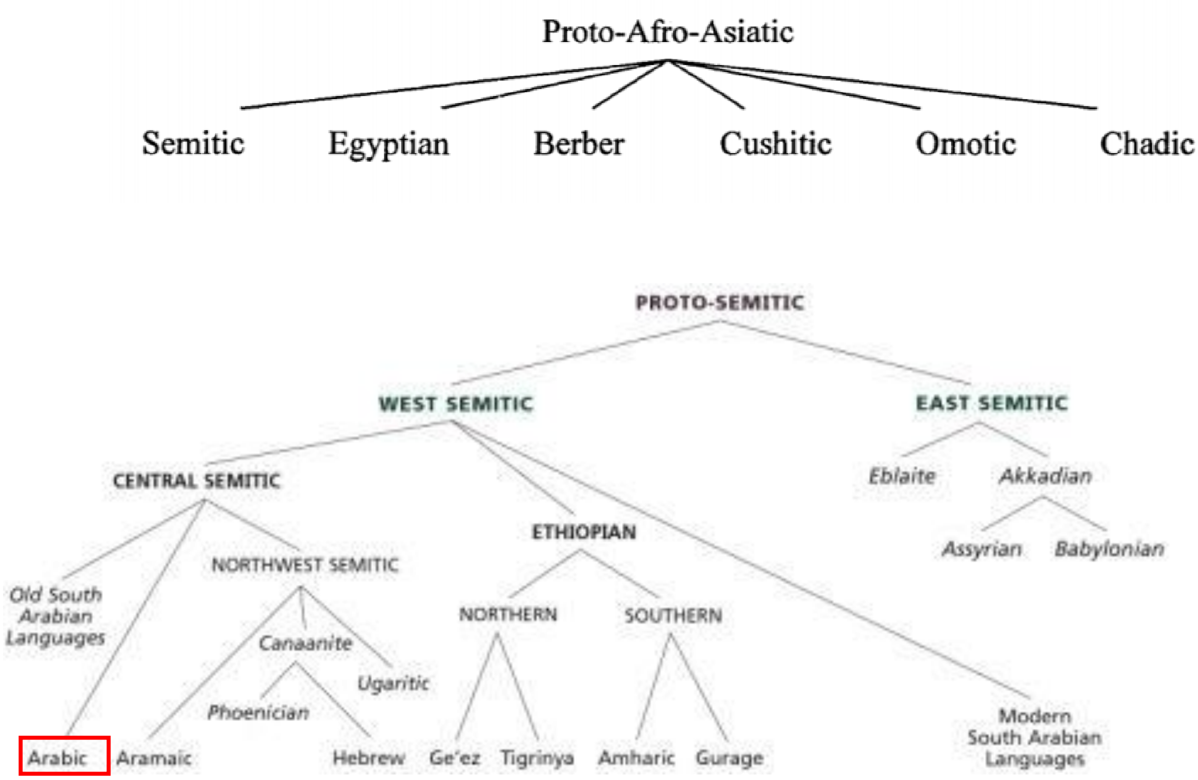

Figure 2. Family tree of Afro-Asiatic languages showing the Semitic branch and the location of Arabic. Image taken from "Etymological Study of Semitic Languages (Chapter Two)" (2009)

Linguistic Distance. When comparing the similarity between two languages, researchers often measure their degree of lexical similarity. According to Ethnologue's method of lexical similarity, English has a lexical similarity of 27% to French but has a similarity of 60% to German (García & De Souza, 2014). As can be seen in Figure 1, English is on the Germanic branch with German, while French is on the Italic branch. That is, English and German share more similarities than English and French.

Another method of measuring linguistic difference is to train individuals who speak English in a foreign language for a set time and then use the *Ethnologue language family index* (Grimes & Grimes 1993) to rate how difficult or easy it was to learn the new language (lower scores meaning more difficult to learn). These scores represent a potential ranking system for how linguistically different each language is from English. A study by Hartz-Gonzalez and Lindemann (1993) found that compared to English, French scored a 2.50 whereas Arabic scored 1.50 (as cited by Chiswick & Miller, 2005). This finding suggests that Arabic is much more linguistically different from English than French.

Morphological Differences. One of the major differences between English and French from Arabic is morphology, or words are formed in each language. Composed of both a lexical root and pattern morpheme, Arabic also often uses inflectional affixes (Ryding, 2014). The infixes used are affixes, which are inserted inside a word stem (the base of a word). A common example of this language structure is using the root “K-T-B” which represents the concept of writing. When combined with the word pattern “maCCaCa” the word generated is *maktaba* or place of writing (Verseteegh, 2014). The forming of words through a combination of morphemes in a linear sequence reflects concatenative morphology. Forming words by modifying the root rather than combining morphemes linearly refers to non-concatenative morphology (Ryding, 2014). Although Arabic contains a mixture of both non-concatenative and concatenative morphological processes, it is predominately characterized by its non-concatenative structure. English and French are both concatenative languages, meaning that words are generated by putting two morphemes together. For example, English and French often use prefixes and suffixes that attach to either the beginning or end of a word stem to form either a new word or a new form of the same word (e.g., happy can become unhappy or happiness; Brinton & Brinton 2010; Fejzo 2016). In English and French infixes do not occur naturally as part of the language (Hamdallah, 1992), although people may generate them while swearing or being emphatic (e.g., Abso-freaking-lutely).

Cognitive Benefits of Bilingualism

As early as the 1960s, research has suggested that bilinguals may experience cognitive advantages over monolinguals, particularly in tasks involving problem solving and creativity (Bain, 1975; Kessler & Quinn, 1987; Peal & Lambert, 1962). Recent research has focused on the potential cognitive advantages that bilinguals may exhibit compared to monolinguals. These potential cognitive advantages in bilinguals can be explained by two main theoretical views. The first suggests that bilinguals could have enhanced inhibition relative to monolinguals. The second theory proposes that bilinguals may exhibit enhanced conflict-monitoring compared to monolinguals. Firstly, when managing two languages, bilinguals' inhibition skills are enhanced because they must constantly inhibit irrelevant information from the language they are not currently using (Duñabeitia et al., 2013). The constant inhibition occurs because, although only one language is typically used at a time, both languages continue to remain active, requiring the individual to suppress or inhibit the non-target language (Bialystok & Martin, 2004; Green, 1998; Wu & Thierry, 2013). Enhanced conflicting monitoring skills are associated with successful retrieval of the relevant language by suppressing interference from the irrelevant conflicting information (for a review see Hilchey & Klein, 2011). Despite two existing hypotheses it should be noted that conflict monitoring may indirectly work through inhibition (Hilchey & Klein, 2011). It has been suggested that because the two theories are intertwined it may difficult to attribute bilingual cognitive differences to either conflicting monitoring or inhibition independently (Bialystok, Craik, &

Luck, 2012). Both theories suggest that people who are bilingual may exhibit enhanced cognitive abilities compared to people who are monolingual.

The bilingual advantage is typically described in terms of bilinguals' superiority in behavioral measures (i.e., improved performance and reaction time) relative to monolinguals. Initial research suggested that the bilingual advantage was evident in problem-solving and creativity tasks (Bain, 1975; Kessler et al., 1987; Peal & Lambert, 1962). These findings of a bilingual advantage have been extended to a variety of cognitive domains such as inhibitory function (Bialystok, Craik, & Luk, 2008; Carlson & Meltzoff, 2008), executive control (Badzakova-Trajkov, 2008; Prior & Gollan, 2011), cognitive control (Kousaie & Phillips, 2017), and task switching (López Zunini, Morrison, Kousaie, & Taler, 2019). Despite these findings indicating enhanced cognitive processing due to bilingualism, many researchers have reported no such cognitive advantage in bilinguals over monolinguals. One possible reason for these inconsistencies could be due to publication bias.

A recently published study reported that the field of bilingualism experiences a publication bias (de Bruin, Treccani, & Della Sala, 2015). They compared conference abstracts on bilingualism and executive control to published studies and found that the abstracts that supported the bilingual advantage were more likely to be published. Despite this potential file-drawer problem, some recent published studies have reported no bilingual advantage in inhibitory processing (Duñabeitia et al., 2013; Kousaie & Phillips, 2017; Rosselli et al., 2002), conflict monitoring (Gathercole et al., 2014), and executive functioning (Goldman, Negen, & Sarnecka, 2014; Nichols, Wild, Stojanoski, Battista, & Owen, 2020). A study measuring 15 different indicators of executive processing in 109 bilinguals found no group differences between monolinguals and bilinguals on task performance (Paap & Greenberg, 2013).

Furthermore, a recent study reported that there were no significant effects suggesting a bilingual advantage in executive functioning in over 11,000 people (Nichols et al., 2020). Although bilinguals were found to perform better on one (of the 12 tests) and monolinguals performed better on four tests, after controlling for confounding factors these effects disappeared.

Some studies have been able to replicate a bilingual advantage in some (but not all) conditions (Chung-Fat-Yim, Himel, & Bialystok, 2019). Chung-Fat-Yim et al. (2019) completed an adapted flanker task with three blocks (each block containing different rules). Block 1 consisted of a single red or blue arrow signifying the response rule; the blue arrow signaled pressing the button in the direction the arrow was pointed, and red arrow signaled pressing the button in the opposite direction the arrow was pointed. Block 2 was a standard flanker with congruent and incongruent trials (e.g., congruent >>>>>; incongruent >><>>, participants responded by identifying which direction the underlined arrow is pointing). Block 3 contained both flanker and rule trials. This study showed that bilinguals only had faster reaction times than monolinguals during the standard flanker task when responding to incongruent trials (i.e., the two groups did not differ in accuracy or reaction time in the rule-switching or mixed block). These findings suggest that bilinguals may perform better than monolinguals only under specific conditions.

The inconsistencies in the literature could be related to several factors: (1) there may be another cognitive process associated with executive processing that has not been examined; (2) current studies conducted are often completed on bilinguals with similar languages; (3) although few studies have examined older adults, bilingual older adults may be less susceptible to age-related cognitive decline than monolingual older adults because of the bilingual advantage; and/or (4) performance measures alone cannot identify the cognitive processing underlying a behavioral response and may not be sensitive enough to determine if differences between groups are present.

Working Memory. Working memory (WM) was defined in the early 1970s as a cognitive process involved with the ability to simultaneously manipulate and store information in short-term memory (Baddeley & Hitch 1974). Working memory consists of three main components: the phonological loop, the visuospatial sketchpad, and the central executive (Baddeley, 2003, 2012) (See Figure 3 for Baddeley's working memory model). The phonological loop consists of a phonological store to hold verbal (or auditory) information for a few seconds before it fades and the articulatory rehearsal which refreshes the information to keep it from fading (Baddeley, 2003). An example of the articulatory rehearsal would be trying to immediately recall a phone number (Goldstein, 2014). The phonological loop has been associated with language comprehension and word learning, suggesting a possible relationship between working memory and bilingualism (Atkins & Baddeley, 1998; Service, 1992). Visual and spatial information, such as a student finding their way around campus by visualizing a previously read map (Goldstein, 2014), is processed in the visuospatial sketchpad (Baddeley, 2003). Although the relationship between the visuospatial sketchpad and language has not been studied in-depth, the visuospatial sketchpad may be involved with language acquisition surrounding objects (Baddeley, 2003). Lastly, the central executive is an attentionally limited system that controls the information entering the phonological loop and visuospatial sketchpad and determines which component of working memory will process the incoming information (Goldstein, 2014). An additional component (the episodic buffer), is proposed to be a limited capacity store that binds information from long-term memory and other components of working memory into an episodic representation (Baddeley, 2003).

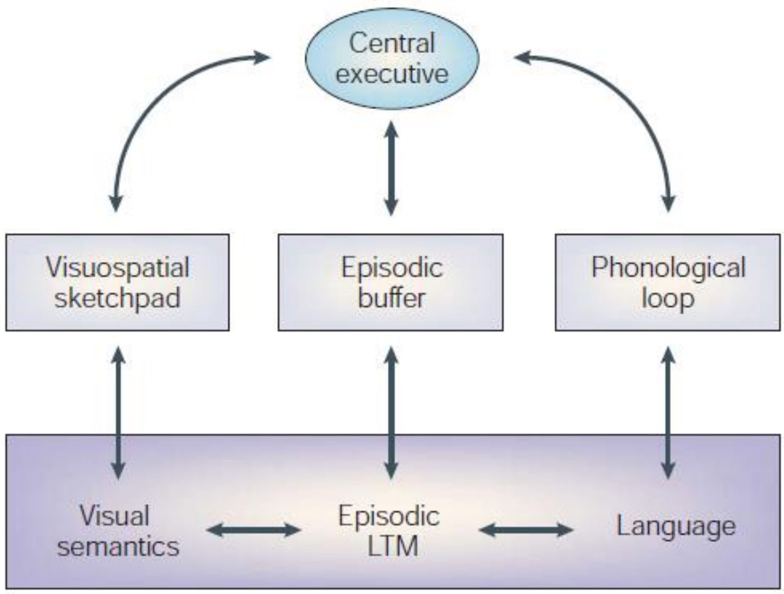

Figure 3: The multi-component of working memory (Baddeley, 2003).

As mentioned, working memory has been associated with language comprehension and language acquisition surrounding objects (Atkins & Baddeley, 1998; Baddeley, 2003). Thus, it is important to examine working memory when studying bilingualism. Given that working memory has been related to language acquisition and proficiency, cognitive differences between monolinguals and bilinguals may be observed in working memory functioning. To date, research investigating the effects of bilingualism on working memory has been inconsistent. Some studies have shown enhanced working memory performance in those who are bilingual (Bialystok & Feng, 2009; Kudo & Swanson, 2014; Morales, Calvo, & Bialystok, 2013) while others have reported no working memory advantage (Blom, Küntay, Messer, Verhagen, & Leseman, 2014; Engel de Abreu & Abreu, 2011; Lukasik, Lehtonen, Soveri, Waris, & Jylkka, 2018; Nichols et al., 2020; Ratiu & Azuma, 2015) compared to monolinguals. These differing results may be because most studies do not account for the participants' L2 usage, participants' proficiency in the L2, or participants' consistency of L2 use (Bialystok & Feng, 2009; Bonifacci & Giombini, 2011; Engel de Abreu & Abreu, 2011; Morales et al., 2013).

A meta-analysis examined the relationship between working memory and bilingualism by including level of proficiency as a continuous variable (Linck, Osthus, Koeth, & Bunting, 2014). This analysis included 79 studies containing over 3,700 participants and almost 750 effect sizes. The authors found a positive relationship between level of proficiency and working memory, with a population effect size of 0.26. After controlling for publication bias, working memory still had a relationship with L2 processing and proficiency. Many of the studies included in the analysis had large sample sizes (approximately 50-100 participants). Even though Papp and Greenberg (2015) previously suggested that a bilingual advantage is observed in underpowered studies, the meta-analysis provides evidence that a bilingual advantage is still observed in larger sample sizes. This meta-analysis also found that the executive control processes that underly working memory are strongly correlated to L2 (Linck et al., 2014). The authors also reported that complex span tasks are stronger predictors of L2 outcomes than simple span measures. Other studies have also reported a similar finding that bilingualism advantages may be most observable when task demands are high (Sullivan, Prescott, Goldberg, & Bialystok, 2016).

A more recent meta-analysis observed that bilinguals exhibited a larger working memory capacity than monolinguals during span tasks (Grundy & Timmer, 2017). A typical span task involves participants being asked to immediately recall a list of random numbers or letters. In the above-mentioned meta-analysis, the authors reviewed 27 independent studies examining over 2900 participants and 88 different effect sizes. The results showed a small to medium effect size of 0.20 in favor of greater working memory capacity for bilinguals than monolinguals (Grundy & Timmer, 2017). In this review, most of the studies included were conducted on young adults; only two out of 27 studies included older adult samples.

Age-Related Cognitive Decline

One reason that the topic of cognitive aging has become of much interest to researchers is because the population of older adults across the world is increasing (World Health Organization, 2015). The main goal of cognitive aging research is to understand age-related cognitive changes and determine how to mitigate these cognitive declines. While vocabulary levels (Salthouse, 2009; Singh-Manoux et al., 2012; Wingfield & Stine-Morrow, 2000) and general knowledge (Harada, Love, & Triebel, 2013) are typically preserved or heightened with age, other cognitive functions such as reasoning (Singh-Manoux et al., 2012), episodic memory (Nilsson, 2003; Singh-Manoux et al., 2012), working memory (Bopp & Verhaeghen, 2005; Daffner et al., 2011), and processing speed (Schaie, 1996) are known to decline with age.

Working memory is one of the cognitive processes which begins to decline early in the aging processes starting in middle age (Bopp & Verhaeghen, 2005; Brockmole & Logie, 2013; Myerson et al., 2003; Park et al., 2002). Changes in working memory due to age may be a result of declines in storage systems and/or declines in the processing underlying working memory (Myerson et al., 2003). The letter-number sequencing task requires people to recall a series of mixed numbers and letters in numerical and alphabetical order. The digit span task presents participants with a list of numbers and the participants are required to recall the list in either the forward or backwards order. Categorizing and reordering both letters and numbers in the letter-number sequencing task is more complex and requires more resources than simply repeating back a list of numbers (Myerson et al., 2003). Several researchers have observed larger group differences between young and older adults during a letter-number sequencing task compared to a forward or backward digit span (e.g., Engle et al., 1999; Myerson et al., 2003). Thus, it can be interpreted that age-related declines are more observable in working memory tasks that are more complex and require more processing.

Several theories of cognitive aging attempt to explain differences in cognition between young and older adults. The most recent model, "the scaffolding theory of aging and cognition" (STAC) explains age differences in cognitive function by incorporating structural, functional, and behavioral factors (Park & Reuter-Lorenz, 2009). This model suggests that an adaptive brain builds compensatory "scaffolding" to maintain performance despite declines in neural structure and function with increased age. This model reflects the brain's attempt to compensate for declines in cognitive functioning and brain structure (e.g., decreased white matter integrity and brain shrinkage) that occur in older adults by recruiting additional brain regions (see Goh & Park, 2009; Park & Reuter-Lorenz, 2009 for a review).

Another model proposes that several cognitive differences between young and older adults occur because of slower processing with increased age (Salthouse, 1996; Salthouse & Ferrer-Caja, 2003). Reduced processing speeds lead to declines in two cognitive mechanisms. The first is the *limited time mechanism*. Early information processing is delayed in older adults. There is thus less (or a "limited") time available for the processing of later cognitive operations. The second mechanism, *simultaneity mechanism*, suggests that the products of earlier processing are lost by the time later processing is complete resulting in processing deficits. A reduction in processing speed leads to decreases in the successful performance of relevant cognitive operations because of limited time.

The inhibition deficit hypothesis is another theory that may explain age-related declines in cognitive function. This hypothesis states that older adults have a decreased ability to suppress/ignore irrelevant information compared to young adults (Rey-Mermet & Gade, 2018). Hasher and Zacks (1988) reported that age-related declines in several tasks, including working memory, episodic memory tasks, and spatial and reasoning abilities, resulted from older adults' inability to remain focused on a primary task. Thus, this hypothesis suggests that age-related cognitive decline is the result of the inability to stay focused and frequently diffuse their attention to irrelevant information. However, a recent meta-analysis of 176 studies comparing young and older adults on inhibition reported that measurable inhibition deficits in age are restricted to a few specific tasks, as several other inhibition measures did not support an inhibition deficit in older adults (Rey-Mermet & Gade, 2018). These findings suggest that declines in cognitive functioning in older adults may result from an additional mechanism other than inhibition.

Another theory explaining age-related cognitive decline is the cognitive resources theory. Reductions in the availability of attentional resources (mental energy) occur with increased age. Difficult tasks require more "mental energy" than simpler tasks. As a result, older adults are less likely to complete more complex tasks effectively than easier ones. For example, older adults are less likely to achieve good performance in a working memory task than a simple span task because of the increased complexity in the former compared to the latter (for review see Luo & Craik, 2008).

Researchers have also found associations between declines in cognitive performance and sensory functioning. There are several theories examining this relationship; Sensory Deprivation hypothesis, the Common-Cause hypothesis, Cognitive Load on Perception hypothesis, and the Information Degradation hypothesis (see Ebaid et al., 2017 for a review). Each hypothesis suggests a relationship between sensory functioning (i.e., auditory and vision) and a decline in cognition. The nature of this relationship could go in either direction. For example, the Cognitive Load hypothesis indicates that declines in cognition lead to declines in perception. On the other hand, the Sensory Deprivation hypothesis states that a lack of sensory input over time leads to cognitive decline. These four hypotheses suggest that with increased age there is a link between sensory functioning and cognition.

Taken together, several well-documented models and hypothesis have been developed to explain age-related cognitive decline. However, there is significant individual variability among older adults' cognitive functioning. These individual differences allow some older adults to cope better with brain pathology and age-related cognitive decline than others.

Cognitive Reserve. Cognitive aging research is challenging because declines in functioning show high levels of individual variability. For example, genetics alone has been shown to account for 60-66% of general cognitive abilities (Harada et al., 2013; Plomin, Haworth, Meaburn, Price, & Davis, 2013) whereas other individual factors such as vision or hearing impairment (Lin et al., 2004) and medication usage (von Moltke, Greenblatt, Romach, & Sellers, 2001) are also known to influence cognitive functioning. Varying levels of cognitive reserve may also influence individual differences within the older adult population. Cognitive reserve is a mechanism that helps the brain cope with brain degeneration (Stern, 2002). Some examples of proxies for cognitive reserve are higher levels of intelligence, engagement in leisure and social activities, and education or occupational attainment (for a review see Stern, 2009, 2002). For example, although two people may have the same neurodegeneration, the person who has higher cognitive reserve will avoid symptoms of brain degeneration longer than the person with lower reserve. In addition to factors such as higher education and engagement in social activities, fluency in two or more languages may also contribute to enhanced cognitive reserve (Bialystok et al., 2007).

Aging and Bilingualism. Since being bilingual may be cognitively demanding, bilingualism could also be a cognitive reserve factor (Craik, Bialystok, & Freedman, 2010). Researchers have argued that bilingualism strengthens the executive control processes (Bialystok & Craik, 2010) that are known to decline with age. Thus, bilingual older adults may exhibit fewer age-related cognitive declines compared to monolingual older adults (Bialystok, Martin, & Viswanathan, 2005; Kousaie & Phillips, 2017). Several studies have shown that lifelong bilinguals exhibit more youthful cognitive functioning compared to monolinguals (Baum & Titone, 2014; Gold, Kim, Johnson, Kryscio, & Smith, 2013). To examine the effects of bilingualism on neural efficiency, Gold et al. (2013) recorded fMRI while participants completed a task-switching paradigm. They found that older adult bilinguals exhibited enhanced performance and less over-recruitment (in left lateral frontal cortex and cingulate cortex) than older adult monolinguals. The authors conclude that lifelong bilingualism can reduce age-related cognitive declines in cognitive control processes involved in task-switching (Gold et al., 2013). Despite these findings, and similar to the research conducted in young adults, some studies report no bilingualism-related cognitive advantages in healthy older adults (Antón, García, Carreiras, & Duñabeitia, 2016; Kousaie & Phillips, 2012a). Thus, there is little agreement as to whether bilingualism offers a cognitive advantage to either young or older adults.

Bialystok et al. (2007) observed that fluency in two languages protects against the development of dementia. This study examined patients from a memory clinic (half monolingual and half bilingual) and found that those who were bilingual had a later onset of dementia by on average, 4.1 years. Other studies have subsequently replicated these findings that being bilingual (or multilingual) offers a protective effect against the onset of Alzheimer's disease (AD) symptoms (Chertkow et al., 2010; Craik et al., 2010). Chertkow and colleagues had the advantage of studying a sample of bilingual and multilingual immigrants and nonimmigrants (2010). While these authors reported a protective effect of bilingualism that delayed the onset of AD symptoms by almost 5 years, the results were only found in a subset of their sample. They also found that immigrants and native-born bilinguals whose first language was French exhibited a protective effect of bilingualism. Non-immigrant English speakers did not show a protective effect (Chertkow et al., 2010). For a thorough review of bilingualism, aging, dementia, and cognitive reserve, see Perani and Abutalebi (2015).

Differences due to bilingualism may not be measurable using behavioral and neuropsychological measures alone. Both these performance measures provide a single score from which researchers must infer both the cognitive processes that led to the response and the cognitive processes that occur following the response. The use of performance measures does not allow for the direct observation of these inferred processes. One way to directly measure the extent of processing that occurred prior to, at the time of, and following the response is event-related potentials (ERPs).

The Event-Related Potential (ERP) Technique

The first recording of human brain activity was done in 1929 by Hans Berger (Berger, 1929). Since then, electroencephalography (EEG) has been used in a wide number of clinical and research applications. For example, continuous raw EEG was recorded in the 1930s to measure spike waves during clinical seizures (Britton et al., 2016). The recording of brain activity with EEG was later introduced into research settings to measure cognitive responses to a stimulus. When an external stimulus is presented, the ongoing "raw" EEG represents a mix of the true "signal" (the brain's response to a stimulus) and random ongoing background "noise" (not related to the stimulus) (Picton, Lins, & Scherg 1995). Additional noise in the data may be related to other sources such as head, body, and muscle movements and other electromagnetic sources from the cables of the EEG equipment. The signal is assumed to be constant with little variability between trials, whereas the noise occurs randomly.

To extract waveforms reflecting the brain's activity during specific processes (the true "signal"), it is necessary to average the raw EEG signal to many (sometimes hundreds) of stimuli. The most powerful method of signal averaging was developed in the 1950s (Dawson, 1954) to reduce the signal-to-noise ratio (S/N ratio; the amplitude of the signal divided by the amplitude of the noise). Averaging the raw EEG to a large number of trials results in the amplitude of the random noise approaching zero, allowing the amplitude of the true signal to emerge. The amplitude of noise is reduced as a function of the square root of n (n= number of trials). After four trials the amplitude of the background noise is reduced by half. If the noise needs to be reduced by a factor of 4 then 16 trials would be required (Picton et al., 1995). For example, the often-recorded P3b component (discussed in section *Cognition and ERPs)* typically measures between 5 and 10 μV embedded with background noise of 10 to 20 μV.

Therefore, in a "worst" case scenario of a 5 μV P3b with background noise of 20 μV the signal to noise ratio is 1:4. To obtain a good signal-to-noise ratio of at least 2:1 would require that the noise be reduced to 2.5 μV. To reduce the noise by a factor of 8 would require 64 trials. In addition to the averaging process there are several other methods to reduce background noise activity such as filtering, thus reducing the number of trials required even further. As can be seen in Figure 2, the EEG segments contain the response to the auditory stimuli as well as random noise, once averaged and filtered the waveform is obtained. From the EEG recording, researchers can extract event-related potentials (ERPs). ERP waveforms are associated with different cognitive processes and can be measured through latency (time to process the stimulus) and amplitude (intensity of the response) (Luck, 2014). These waveforms consist of several functionally and structurally distinct deflections called peaks, waves, or components. ERPs are characterized by positive or negative components that occur at post-stimulus presentation.

ERP components are classified as either sensory (exogenous) or as cognitive (endogenous). Exogenous components are mainly influenced by the physical properties of a stimulus such as intensity, location, colour, and frequency. Thus, as an auditory stimulus increases in intensity, the auditory exogenous N1 component, occurring at about 100 ms, increases in amplitude. The exogenous components usually reflect the early extraction of physical features of the stimulus occurring typically within the first 10 to 100 ms following onset of the stimulus. A pure exogenous component is not affected by cognitive processing. Thus, operations such as attention, consciousness, and personal relevance of the stimulus will not affect the exogenous components. Thus, attending to the auditory channel will not alter the amplitude of the exogenous N1. On the other hand, endogenous components are affected by cognitive processes such as attention, consciousness, relevance, decision-making, and memory (Sutton, Braren, Zubin, & John, 1965). The endogenous components generally occur later, after the extraction of physical features. They are not, however, affected by the physical features of the stimulus. Thus, the detection of a rare and randomly occurring visual stimulus will elicit a late (300 ms+) positivity, labelled the P3, P3b, or P300. The detection of a rare auditory stimulus will elicit the same P3b even though the modality has completely changed. If the participant does not attend (i.e., ignores), the auditory stimuli, then the rare auditory stimulus will not elicit the P3b but it will continue to elicit the earlier N1. In Figure 4, the N1 is a sensory component that is affected by changes to the stimulus itself. For example, if a stimulus that is presented multiple times is a loud tone and then changes to a quiet tone, N1 amplitude will decrease because there is a physical manipulation of the stimulus. However, if there were cognitive processes involved such as requiring the participant to press a button when the quiet tone occurs, the N1 would not change in amplitude or latency. On the other hand, cognitive evoked potentials such as the P3b are influenced by cognitive manipulation rather than sensory changes. P3b will only be elicited when the participant attends to the sequence and detects the rare tone.

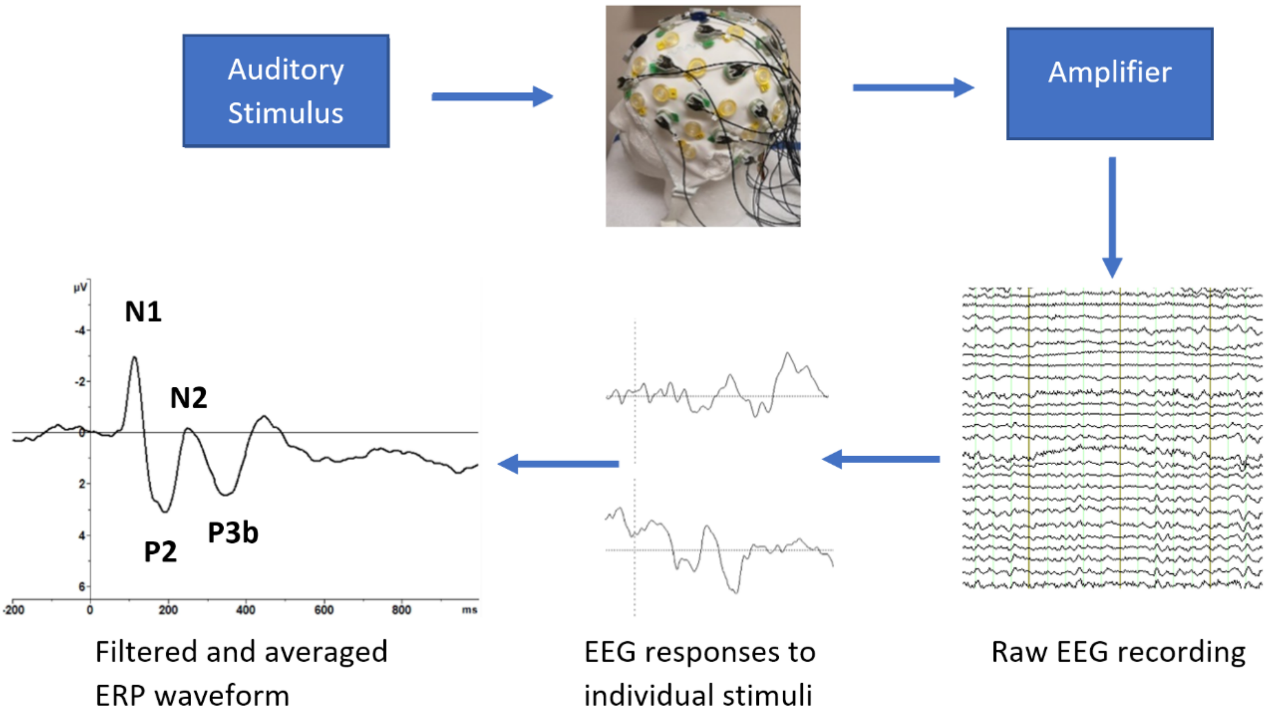

Figure 4: **Illustration of stimulus presentation and ERP generation.** The stimulus is presented multiple times as brain activity is recorded through electrodes placed on the scalp. This activity (raw data) is monitored and recorded by a computer which then can be averaged offline across all trials to generate the cleaned and averaged data.

The classic cognitive component, the P300 (i.e., P3 or P3b), was discovered in 1965 when participants were presented with tasks in which they could predict which stimulus they would be shown (Sutton et al., 1965). Sutton et al. (1965) presented clicks or brief light flashes in pairs to participants. The first of the pair served as a cue and the second of the pair was the test stimulus. There were two kinds of pairs: 1) the cue was followed by a test stimulus which was always a sound or always a light, thus the participant was able to predict which stimulus would be shown; 2) in the second kind of pairs the cue was followed by either a sound or a light, thus the participant was unable to predict which stimulus was going to be presented next. The authors found that an evoked potential (occurring around 300 ms; now known as the P300) varied as a function of whether the participants could predict the test stimulus. The P300 was larger in cases where the participants were uncertain of the test stimulus. On the other hand, the earlier exogenous visual components remain unchanged.

Unfortunately, there are several naming conventions for ERPs. Firstly, components can be are named based on their polarity (positive or negative) and latency. For example, the P300 component is a positive deflection that occurs approximately 300 ms post-stimulus presentation. However, because the P300 can occur in a wide latency (300-600 ms) researchers often name the components based on order of sequence. The P300 is also labelled as the P3 because it is the third major positive peak that will be observed in the waveform. Another issue with labelling conventions is that newer components may subsequently be discovered that occur between two existing components. For example, following the discovery of the positivity labelled P3 by Sutton (1965), another positivity occurring between P2 and P3 was discovered. This positivity like the P3 was elicited to a rare stimulus, but it occurred even when subjects were not attending. The two late positivities elicited by rare stimulus events were subsequently labeled P3a and P3b. ERP components may also be named based on their functional significance (Picton et al., 1995). A common example is the error-related negativity, which occurs when a participant makes an *obvious* incorrect response.

The ERP components may also have different scalp distributions (where the component is maximum and minimum). For example, the P3a described is maximum over fronto-central areas of the scalp while the P3b is maximum over parietal areas of the scalp. Because different ERP components may be largest over different areas of the scalp, EEG activity is usually recorded from multiple electrode sites and placed according to a standardized naming system (10-20 system) (Jasper, 1958). A drawback of the 10-20 system is that electrodes cannot be placed close together, thus the 10-10 system was developed to allow electrodes to be placed at the intermediate positions (Pivik et al., 1993). Electrodes are labeled according to the region where they are placed (FP = Frontal Polar F= Frontal, C = Central, P = Parietal, T = Temporal, O = Occipital), with odd numbers placed over the left hemisphere and even numbers over the right hemisphere. For example, the electrode F4 would be placed on the right frontal scalp while the F3 would be placed at the left frontal scalp location. The larger the number, the more lateral and inferior will be the placement. Thus, F8 would be more inferior on the frontal scalp than F4. Figure 5 shows an example of an electrode placement.

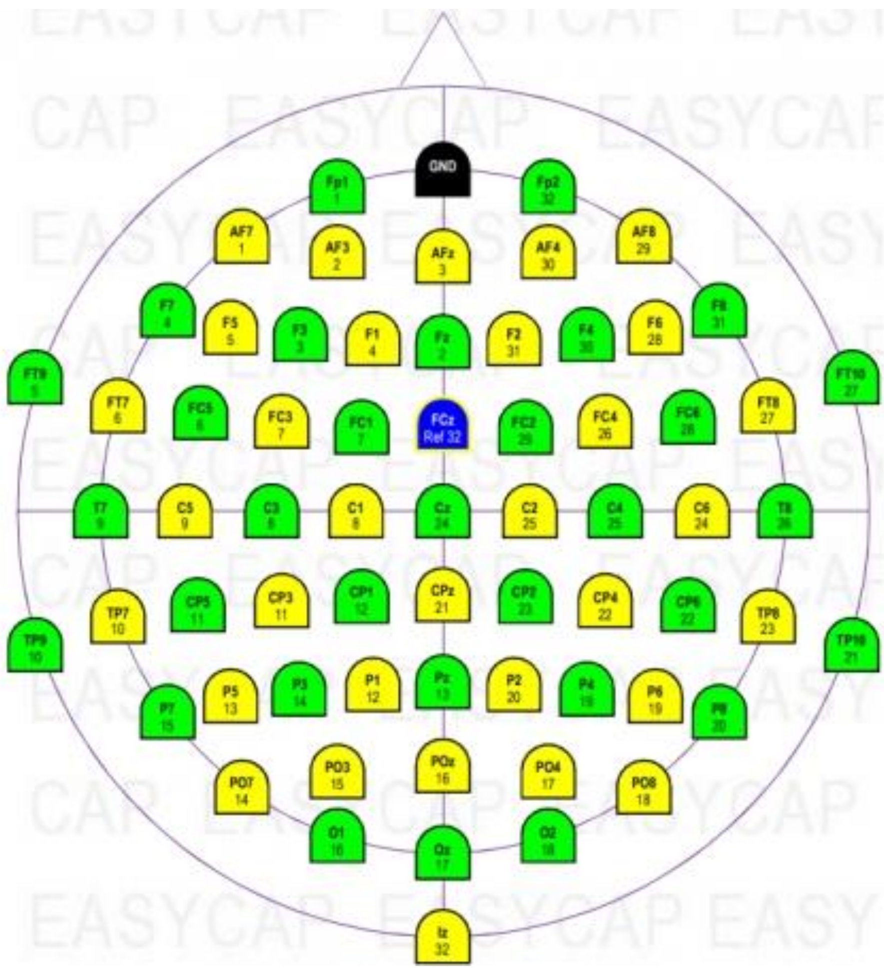

Figure 5: **Standardized 10-10 placement of EEG electrodes.** Image taken from Brain Vision (Brain Products, GmbH, Munich, Germany).

Cognition and ERPs. In 1964 a component called the "contingent negative variation" or CNV was discovered (Walter, Cooper, Alderidge, McCallum, & Winter, 1964). Participants were presented with a warning signal followed about 1 to 2 seconds later by a single target stimulus (participants were asked to press a button as evidence that they had attended to the sequence and detected the target). During the delay between the warning signal and the target stimulus, the development of a long-lasting (or "slow") large negative wave was observable over frontal regions of the scalp. Because this waveform occurred between the two stimuli (i.e., in the absence of any physical stimulus), it could not reflect "exogenous" activity. Instead, this negative waveform reflected the subjects' preparation for, or psychological expectancy of the future target. The subject learned that the occurrence of the target was contingent on the presentation of the initial warning stimulus. The discovery of an ERP component that did not reflect sensory processing lead to the exploration of other cognitive ERP components.

The P2 component is a fronto-central maximal positive ERP waveform that peaks approximately 150-300 ms post-stimulus presentation (Luck, 2014). The visual evoked P2 was conceptualized as a marker of top-down control that indexes stimulus salience (Riis et al., 2009). A larger P2 amplitude is evoked for target stimuli (than for non-target stimuli), and when the targets are relatively infrequent. The P2 has also shown to be sensitive to stimulus characteristics like color and size (Riis et al. 2009). Additionally, the P2 is thought to be related to attention allocation in working memory functioning (Finnigan, O'Connell, Cummins, Broughton, & Robertson, 2011; Lijffijt et al., 2009). In previous working memory studies, a decline in P2 amplitude has been associated with decreased performance. More specifically, smaller P2 amplitudes occur as a result of decreased attentional allocation and lower working memory performance (Finnigan et al., 2011).

The present work also examines the N200, also known as the N2 or N2b. This component is a fronto-central negative waveform that occurs 200-350 ms following stimulus presentation (Folstein & Van Petten, 2008). This component has been shown to be affected by ease of perceiving differences between two stimuli (Bennys, Portet, Touchon, & Rondouin, 2007; Folstein & Van Petten, 2008; Patel & Azzam, 2005). This may be related to the concept of "effort". A difficult task is presumed to required greater cognitive effort resulting in an increased N2. Previous studies measuring the N200 during a working memory task have shown that the N200 amplitude continually increases with task difficulty (Patel & Azzam, 2005; Pinal & Díaz, 2014). This increase with task difficulty could be interpreted as more attention and effort needed to retrieve the memory of the past stimulus and determine if the current target matches the previous one.

There are several ERP components in the time range of the P3 (e.g., P3a and P3b). This thesis will focus on the P3b (P300), because this component is one of the most widely studied due to its involvement in many cognitive processes. Initially, Donchin (1981) posited that the P3b indexes brain activities involved with the updating of working memory. Johnson (1986) also proposed that the P3b amplitude varies based on the interaction of three dimensions: 1) subjective probability, 2) stimulus meaning, and 3) information transmission. Now, in addition to the updating of working memory the P3b is suggested to be involved in cognitive control, memory processing, and attention (Donchin, 1981; Mertens & Polich, 1997; Polich, 2007). The P3b is a positive-going waveform that occurs 300-400 ms post-stimulus presentation when a participant is actively engaged in the detection of a target (Picton, 1992). However, the timing of the P3b can range from 250-900 ms following stimulus presentation. The latency of the P3b varies between tasks because of task demands. Following an easy task, the latency will be relatively short whereas tasks that are more demanding will elicit a longer latency P3b. A longer latency is elicited in the more difficult conditions as more processing resources are needed for task completion than in easier tasks (see Polich 2007 for a review).

The P3b amplitude will vary between tasks that alter stimulus attention and measure memory processes. In memory tasks, as memory load increases the amplitude decreases because of increase task demands (see Polich 2007 for a review). The P3b amplitude may also reflect the availability of resources for task completion. Larger amplitudes may be observed in undemanding task conditions, as task difficulty increases P3b amplitude becomes smaller as more resources are used (Kok, 2001; Polich, 2007). Previous studies on working memory have shown that high performers have increased (rather than decreased) amplitudes as task difficulty increases, which has been interpreted as high performers having additional resources available for task completion (Daffner et al., 2011).

Bilingualism and ERPs. Several researchers have incorporated the use of electrophysiological tools to examine cognitive processing differences between monolinguals and bilinguals. Using neuroimaging techniques is an appropriate approach because if bilingualism does lead to a cognitive advantage then structural and functional differences should be found in the regions that underlie those processes. Brain structure and cognitive functioning are known to be influenced by learning an additional language (García-Pentón, García, Costello, Duñabeitia, & Carreiras, 2016; Li, Legault, & Litcofsky, 2014).

Neural changes in bilinguals are typically found in the regions associated with language processing and control. Using MRI, researchers have observed differences in grey matter volume (Mårtensson et al., 2012) and brain structure (Burgaleta, Sanjuán, Ventura, Sebastián-Gallés, & Ávila, 2016; Pliatsikas, DeLuca, Moschopoulou, & Saddy, 2017) between monolinguals and bilinguals. Mechelli et al. (2004) found that bilinguals have increased grey matter density in the left inferior parietal cortex compared to monolinguals. This increased density is not surprising given that the inferior parietal cortex has been associated with second language acquisition and performance on verbal fluency tasks (Mechelli et al., 2004). With regard to functioning, bilinguals have been found to have more activity in the prefrontal and inferior frontal regions than monolinguals (Kovelman, Baker, & Petitto, 2008). Several studies have also shown that structural and functional differences are sensitive to factors of individual variability such as age of acquisition (DeLuca, Rothman, Bialystok, & Pliatsikas, 2019; Nichols & Joanisse, 2016; Rossi, Cheng, Kroll, Diaz, & Newman, 2017) and L2 proficiency (Abutalebi et al., 2013; DeLuca et al., 2019; Mamiya, Richards, Coe, Eichler, & Kuhl, 2016). For a review of brain structure and functioning differences between monolinguals and bilinguals, see García-Pentón et al. (2016) and Wong, Yin, and O'Brien (2016). ERPs have also been used in the study of bilingualism to examine whether bilinguals display cognitive advantages over monolinguals.

One study examined ERP differences between monolinguals and bilinguals during three cognitive tasks (Stroop, Simon, and Flanker) measuring conflict monitoring, resource allocation, stimulus categorization, and error monitoring (Kousaie & Phillips, 2012b). These researchers observed that in some tasks, bilinguals exhibited smaller N2 and P3b amplitudes than monolinguals. Behavioral performance was similar across the groups and therefore the ERP differences may not reflect a bilingual advantage per se, but rather differences in cognitive processing between the groups. Another study examining task-switching differences observed that: 1) bilinguals exhibited larger N2 amplitudes compared to monolinguals, 2) bilingual older adults exhibiting smaller P3b amplitudes than monolingual older adults, and 3) bilingual and monolingual young adult P3b amplitudes did not differ (López Zunini et al., 2019). Similar to Kousaie and Phillips (2012b), these authors interpreted ERP differences as reflecting processing differences between monolinguals and bilinguals. Additionally, the differences between older adult bilingual and monolinguals (and no differences in young adults) was interpreted as bilinguals adopting different processing strategies with increased age.

Several other studies have reported larger P3b amplitudes in bilinguals compared to monolinguals (Barac, Moreno, & Bialystok, 2016; Moreno, Wodniecka, Tays, Alain, & Bialystok, 2014; Sullivan, Janus, Moreno, Astheimer, & Bialystok, 2014). Some of these studies have reported ERP differences between bilinguals and monolinguals in the absence of behavioral differences (Barac et al., 2016; Grundy, Anderson, & Bialystok, 2017; Kousaie & Phillips, 2012b). Taken together, these results suggest that bilinguals may exhibit different processing strategies than monolinguals in the absence of a behavioral bilingual advantage.

Aging and ERPs. In addition to declines in cognitive processes, older adults may also exhibit changes in brain activity. Several well-established theories and models regarding brain activity differences between young and older adults exist:

1) Older adults compensate for age-related cognitive declines by recruitment of additional brain regions (Cabeza, Anderson, Locantore, & McIntosh, 2002; Grady et al., 1994; Stern et al., 2000). This compensation is thought to then reduce or potentially eliminate any behavioral performance declines in older adults.
2) There have also been studies showing increased activation in some regions with deactivations in others (Milham et al., 2002). Changes in brain activation are often reflected by reduced activity in occipitotemporal regions but increased activity in anterior regions. This change is referred to as the Posterior-to-Anterior Shift in

Aging (PASA; Davis, 2008). Increased activation in frontal regions reflects an adaptive mechanism to compensate for aging brain declines in posterior areas.

3) Many researchers have also observed a pattern of activation of compensatory recruitment mediated by the prefrontal cortex (Cappell, Gmeindl, & Reuter-Lorenz, 2010; Reuter-Lorenz & Cappell, 2008). This pattern of change (termed the Compensation-Related Utilization of Neural Circuits Hypothesis; CRUNCH; Reuter-Lorenz and Lustig, 2005) suggests that older adults recruit additional neural resources at lower levels of task demand; the increased activation is referred to as over-recruitment or over-activation. Extra resources allow older adults to maintain similar performance to their younger counterparts. However, when the task becomes even more difficult, older adults may not have sufficient additional resources to successfully complete the task and brain activity and performance may subsequently decrease.
4) Another model examining the effects of aging on brain activity is Hemispheric Asymmetry Reduction in Older adults (HAROLD; Cabeza, 2002). This model postulates that during cognitive tasks, older adults show a more bilateral pattern of prefrontal cortex (PFC) activity than young adults. This pattern of activation may serve as a compensatory function or may reflect a dedifferentiation process.

The study of these neural processing in age using ERPs has been a popular area of research. A PsycINFO search returns over 1200 articles using the keywords “aging”, “older adults”, “ERPs”, and “event-related potentials” since the year 2000. The present work focuses on age-related changes in the P2, N2, and P3b.

Research investigating changes in P2 amplitude and latency during visual tasks due to age has been relatively inconsistent. While some studies have reported decreased amplitude due to age in oddball (O'Connell et al., 2012) and working memory tasks (Finnigan et al., 2011; Missonnier et al., 2004), others have observed increases in P2 amplitude in older adults during working memory processing, (McEvoy, Pellouchoud, Smith, & Gevins, 2001) relative to young adults. However, McEvoy et al. (2001) did not find performance differences between young and older adults. On the other hand, Missonnier et al. (2004) found that older adults had poorer performance than young adults. These results suggest that older adults who have larger P2 amplitudes may be successfully compensating for age-related cognitive declines. During an n-back task, older adults who exhibited larger P2 amplitudes than young adults maintained similar performance to the young adults, while those who did not exhibit larger P2 amplitudes showed lower behavioral performance than young adults (Morrison, Kamal, & Taler, 2019).

Several studies have investigated the effects of age on the N2 component, with many reporting a delay in N2 latency (e.g., Fernandez, Monacelli, & Duffy, 2013; Gajewski & Falkenstein, 2014) and a decrease in amplitude with increasing age (Pekkonen et al., 1996; Riis et al., 2009). In a study investigating the effects of novel stimuli on young and older adults, a large N200 amplitude was elicited in young but not older adults (Czigler & Balázs, 2005). Age differences in this component may reflect a reduction in controlled processes that require selective attention (Amenedo & Díaz, 1998). During an n-back working memory task examining differences between young adults and older adults, one study found that older participants generated a much smaller N2 than their younger counterparts (Daffner et al., 2011). A reduced N2 in older relative to young adults was replicated in another study looking at working memory performance using an n-back task (Morrison, Kamal, & Taler, 2019).

Declines in N2 amplitude might signify a decline in working memory (Daffner et al., 2011).

Clear evidence exists for age-related differences in the P3b, with consistent decreases in amplitude and delayed latencies being observed (for reviews see Friedman, 2012; Polich, 1996) often regardless of the task being used. Prolonged P3b latency in older adults (Gajewski & Falkenstein, 2014; Saliasi, Geerligs, Lorist, & Maurits, 2013; Vallesi, 2011) suggests increased time and processing resources needed for task completion. P3b amplitude differences are also observed with increased age. This component has shown scalp distribution differences when examining age-related changes. For example, a smaller P3b has been observed in older adults at parietal sites (Hogan et al., 2012; Lorenzo-López, Amenedo, Pascual-Marqui, & Cadaveira, 2008; McEvoy et al., 2001; Saliasi et al., 2013; Wild-Wall, Falkenstein, & Gajewski, 2011) whereas a larger P3b amplitude has been observed over frontal sites in older compared to young adults (Daffner et al., 2011; Fujiyama, Garry, Martin, & Summers, 2010; O'Connell et al., 2012; Saliasi et al., 2013; Vallesi, 2011). The decline at parietal sites may be associated with less efficient performance (Saliasi et al., 2013) and attenuation of cognitive resources (Gajewski & Falkenstein, 2014). Consistent with the PASA model, the increase in frontal region amplitude suggests that older adults may recruit additional resources to compensate for parietal declines in compared to young adults to complete the same task.

The Current Project

Previous research examining whether bilinguals exhibit cognitive advantages over those who are monolingual has been inconsistent. This project was designed to further explore the effects of bilingualism on cognitive functioning and brain activity. Part 1(Study 1 and 2) of the thesis has two main objectives: 1) to investigate the effects of bilingualism on working memory capacity in young adults, and 2) to examine the underlying neural mechanisms associated with working memory processing. Part 2 (Study 3 and 4) of the thesis aimed to examine the effects of both bilingualism and age on working memory using both behavioural and ERP measures of processing during this task. Part 3 (Study 5) was designed to examine if linguistic distance between languages influences whether a bilingual advantage is observed in working memory performance and ERP measures.

The current studies were conducted at the Bruyère Research Institute with ethical approval from both the University of Ottawa and Bruyère Research Institute. Participants provided informed written consent and were compensated $10 per hour.

Rationale for Current Project

Current research attempting to understand the effects of bilingualism on cognitive functioning and its underlying neural activity has been inconsistent. Unfortunately, there are several topics within this field of research that have yet to be investigated in-depth. Few studies have examined whether cognitive processing (as measured by ERPs) differs between monolinguals and bilinguals. Additionally, more research is needed to examine whether linguistic distance between a bilingual’s two languages influences cognitive functioning. The groups most often studied (young adults) may not exhibit cognitive advantages from being bilingual because they are at the peak of their cognitive functioning. Older adults who experience age-related decline may thus show benefits of being bilingual. The current studies were designed to address these gaps in the literature by incorporating electrophysiological measures, a sample of Arabic-English bilinguals, and an older adult sample.

Part 1 Rationale. The following manuscripts entitled, “The influence of bilingualism on working memory event-related potentials” and “Monolinguals and bilinguals respond differently to a delayed matching-to-sample task: an ERP study” examine whether the processes associated with working memory differs between monolingual and bilingual young adults. Part 1 was based on the hypothesis that bilinguals exhibit enhanced cognitive functioning compared to monolinguals. Several meta-analyses have suggested that bilinguals show enhanced working memory capacity compared to monolinguals. To expand on the meta-analyses, Paradigms 1 and 2 were designed to examine if ERP differences are present between young adult monolinguals and bilinguals[3]. No studies have investigated whether working memory differs between monolinguals and bilinguals using ERPs. Previous research examining the effects of bilingualism on working memory has strictly used performance measures, which as mentioned earlier, the cognitive processes associated with the performance measure can only be inferred after the participant has responded. Some of the aforementioned studies have used fMRI methodology. While this technique does provide excellent spatial resolution, allowing the precise regions of brain activation, temporal resolution is poor. Again, differences in processing need to be inferred. The present studies employ a unique measure, ERP methodology, to overcome these limitations. ERPs should provide a better understanding of precisely when cognitive processing differs between bilinguals and monolinguals. Again, it is possible that the performance and physiological measures may provide different results.

In order to determine when cognitive processing differs a series of ERP components were measured. The P2 is a fronto-central component occurring between 150-300 ms, the N2

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[3] It should be noted that most participants completed both the DMS and n-back tasks, resulting in a high degree of overlap between the samples in Part 1, 2, and 3.

is a frontocentral occurring around 200-350 ms, and the P3b is a parietal maximal component between 300-600 ms. However, because the time ranges at which the components occur vary depending on task conditions and age visual inspection will be used to identify the components. These components were chosen because they are sensitive to the cognitive processes involved in working memory, aging, and bilingualism.

Part 2 Rationale. Two studies were run: "ERP measures of the effects of age and bilingualism on working memory performance" and "Bilinguals exhibit ERP differences in the absence of a "bilingual advantage"". These studies use ERP measures to study the effects of age and bilingualism on working memory. Although previous research has examined the effects of age on working memory and the effects of age on bilingualism, no study has examined the interaction of age and bilingualism on working memory using both behavioral measures and ERPs. The goal of Part 2 was to determine whether bilingual and monolingual older adults exhibit differences in the ERPs underlying working memory.

The intent of Part 1 and 2 was to measure ERP in young and older adults during working memory tasks. To reduce the intra-group variability, strict participant inclusion and exclusion criteria was employed. Many studies have not controlled for factors such as age of proficiency of their bilingual participants, which second language the participant is proficient in, and whether a participant is a "true" monolingual. Bilingual participants had to be English-French bilinguals who were proficient in both languages before 13 years of age and monolinguals could only have "very-little ability" in a second language.

Part 3 Rationale. The third part of this dissertation includes a paper entitled, "ERP differences in working memory between English monolinguals, English-French bilinguals, and Arabic-English bilinguals". This manuscript was designed to determine if linguistic distance influences the “bilingual advantage”. Most studies examining the influence of bilingualism on cognitive functioning focus on languages that are linguistically similar having relatively small linguistic distances between the languages. To my knowledge, only one study has examined differences in working memory in monolinguals and Arabic-English bilinguals. This study was however, carried out in children and moreover, did not use ERP methodology. The study presented in Part 3 again used ERP to determine if there are differences in ERPs between English monolinguals, English-French bilinguals, and Arabic-English bilinguals during working memory tasks.

The main research questions addressed in the present work are:

1. Does bilingualism enhance performance on working memory tasks (i.e., accuracy and reaction time)?

2. Are age-related declines in working memory mitigated by bilingualism?

3. Do ERPs differ between monolinguals and bilinguals during a working memory task?

4. Does linguistic distance between languages influence whether a bilingual advantage is observed?

References

Abutalebi, J., Della Rosa, P. A., Ding, G., Weekes, B., Costa, A., & Green, D. W. (2013). Language proficiency modulates the engagement of cognitive control areas in multilinguals. *Cortex*, 49(3), 905-911. https://doi.org/10.1016/j.cortex.2012.08.018

Abutalebi, J., Della Rosa, P. A., Green, D. W., Hernandez, M., Scifo, P., Keim, R., Cappa, S. R., & Costa, A. (2012). Bilingualism tunes the anterior cingulate cortex for conflict monitoring. *Cerebral Cortex*, 22(9), 2076–2086. doi:10.1093/cercor/bhr287

Amenedo, E., & Dıaz, F. (1998). Automatic and effortful processes in auditory memory reflected by event-related potentials. Age-related findings. *Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section*, *108*(4), 361-369. https://doi.org/10.1016/S0168-5597(98)00007-0

Anderson, J. A., Mak, L., Chahi, A. K., & Bialystok, E. (2018). The language and social background questionnaire: Assessing degree of bilingualism in a diverse population. *Behavior Research Methods*, *50*(1), 250-263. https://doi.org/10.3758/s13428-017-0867-9

Antón, E., García, Y. F., Carreiras, M., & Duñabeitia, J. A. (2016). Does bilingualism shape inhibitory control in the elderly? *Journal of Memory and Language*, *90*, 147-160. https://doi.org/10.1016/j.jml.2016.04.007

Atkins, P. W., & Baddeley, A. D. (1998). Working memory and distributed vocabulary learning. *Applied Psycholinguistics*, *19*(4),537-552. https://doi.org/doi:10.1017/S0142716400010353

Baddeley, A. (2012). Working memory: Theories, models, and controversies. *Annual Review of Psychology*, 63, 1–29. https://doi.org/10.1146/annurev-psych-120710-100422

Baddeley, A. (2003). Working memory: looking back and looking forward. *Nature Reviews. Neuroscience*, *4*(*10*), 829-839.

Baddeley, A. (2000). The episodic buffer: a new component of working memory? *Trends in Cognitive Sciences*, 4(11), 417-423.https://doi.org/10.1016/S1364-6613(00)01538-2

Baddeley, A. D., & Hitch, G. (1974). Working Memory. In Gordon H. Bower (Ed.), *Psychology of Learning and Motivation*,8,47-89. Academic Press.

Badzakova-Trajkov, G., 2008. A behavioural and functional imaging investigation of Stroop task performance in late proficient bilinguals. Doctoral Dissertation, *The University of Aukland*

Bain, B. (1975). Toward an integration of Piaget and Vygotsky: Bilingual considerations. *Linguistics, 13*(*160*), 5–20.

Barac, R., Moreno, S., & Bialystok, E. (2016). Behavioural and electrophysiological differences in executive control between monolingual and bilingual children. *Child Development, 87*(*4*), 1277–1290. DOI: 10.1111/cdev.12538

Baum, S., Titone, D., 2014. Moving toward a neuroplasticity view of bilingualism, executive control, and aging. *Applied Psycholinguist*, 35, 857–894. https://doi.org/10.1017/S0142716414000174

Bennys, K., Portet, F., Touchon, J., & Rondouin, G. (2007). Diagnostic value of event-related evoked potentials N200 and P300 subcomponents in early diagnosis of Alzheimer's disease and mild cognitive impairment. *Journal of Clinical Neurophysiology, 24*(*5*), 405–412.

Berger, H. (1929). Über das elektroenkephalogramm des menschen. *Archiv für Psychiatrie und Nervenkrankheiten*, *87*(1), 527-570.

Bialystok, E., & Martin, M. M. (2004). Attention and inhibition in bilingual children: Evidence from the dimensional change card sort task. *Developmental Science, 7*(*3*), 325–339.

Bialystok, E., Craik, F. I. M., Grady, C., Chau, W., Ishii, R., Gunji, A., et al. (2005). Effect of bilingualism on cognitive control in the Simon task: evidence from MEG. Neuroimage 24, 40–49. doi: 10.1016/j.neuroimage.2004. 09.044

Bialystok, E., Martin, M. M., & Viswanathan, M. (2005). Bilingualism across the lifespan: The rise and fall of inhibitory control. *International Journal of Bilingualism*, 9(1), 103-119. https://doi.org/10.1177/13670069050090010701

Bialystok, E., Craik, F. I., & Freedman, M. (2007). Bilingualism as a protection against the onset of symptoms of dementia. *Neuropsychologia*, *45*(2), 459-464. https://doi.org/10.1016/j.neuropsychologia.2006.10.009

Bialystok, E., Craik, F., & Luk, G. (2008). Cognitive control and lexical access in younger and older bilinguals. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *34*(4), 859. https://doi.org/10.1037/0278-7393.34.4.859

Bialystok, E., & Feng, X. (2009). Language proficiency and executive control in proactive interference: Evidence from monolingual and bilingual children and adults. *Brain and Language*, *109*(2-3), 93-100. https://doi.org/10.1016/j.bandl.2008.09.001

Bialystok, E., & Craik, F. I. (2010). Cognitive and linguistic processing in the bilingual mind. *Current Directions in Psychological Science*, *19*(1), 19-23. https://doi.org/10.1177/0963721409358571

Bialystok, E., Craik, F. I., & Luk, G. (2012). Bilingualism: consequences for mind and brain. *Trends in Cognitive Sciences*, 16(4), 240-250.https://doi.org/10.1016/j.tics.2012.03.001

Bialystok, E., Craik, F. I., Binns, M. A., Ossher, L., & Freedman, M. (2014). Effects of bilingualism on the age of onset and progression of MCI and AD: Evidence from executive function tests. *Neuropsychology*, *28*(2), 290. DOI: 10.1037/neu0000023

Blom, E.,Küntay,A. C., Messer, M.,Verhagen, J.,&Leseman, P. (2014). The benefits of being bilingual:Working memory in bilingual Turkish–Dutch children. *Journal of Experimental Child Psychology, 128,* 105–119.

Bonifacci, P., Giombini, L., Bellocchi, S.,&Contento, S. (2011). Speed of processing, anticipation, inhibition and working memory in bilinguals. *Developmental Science, 14*(*2*), 256–269. https://doi.org/10.1111/j.1467-7687.2010.00974.x

Bopp, K. L., & Verhaeghen, P. (2005). Aging and verbal memory span: A meta-analysis. *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences*, *60*(5), P223-P233. https://doi.org/10.1093/geronb/60.5.P223

Brockmole, J. R., & Logie, R. H. (2013). Age-related change in visual working memory: a study of 55,753 participants aged 8–75. *Frontiers in psychology*, *4*, 12. https://doi.org/10.3389/fpsyg.2013.00012

Britton, J. W., Frey, L. C., Hopp, J. L., Korb, P., Koubeissi, M. Z., Lievens, W. E., ... & St, E. L. (2016). Electroencephalography (EEG): An introductory text and atlas of normal and abnormal findings in adults, children, and infants.

Brinton, L. J., & Brinton, D. (2010). *The linguistic structure of modern English*. John Benjamins Publishing.

Burgaleta, M., Sanjuán, A., Ventura-Campos, N., Sebastian-Galles, N., & Ávila, C. (2016). Bilingualism at the core of the brain. Structural differences between bilinguals and monolinguals revealed by subcortical shape analysis. *NeuroImage*, *125*, 437-445.

Cabeza, R. (2002). Hemispheric asymmetry reduction in older adults: the HAROLD model. *Psychology and Aging*, 17(1), 85. https://doi.org/10.1037//0882-7974.17.1.85

Cabeza, R., Anderson, N. D., Locantore, J. K., & McIntosh, A. R. (2002). Aging gracefully: compensatory brain activity in high-performing older adults. *Neuroimage*, *17*(3), 1394-1402. https://doi.org/10.1006/nimg.2002.1280

Calvo, N., Ibáñez, A., & García, A. M. (2016). The impact of bilingualism on working memory: a null effect on the whole may not be so on the parts. *Frontiers in Psychology*, *7*, 265. https://doi.org/10.3389/fpsyg.2016.00265

Canada Census, (1996). Retrieved from: https://doi.org/93F0024XDB96003

Canada Census, (2017). Retrieved from http://www12.statcan.gc.ca/census-recensement/2016/as-sa/98-200-x/2016009/98-200-x2016009-eng.cfm

Cappell, K. A., Gmeindl, L., & Reuter-Lorenz, P. A. (2010). Age differences in prefontal recruitment during verbal working memory maintenance depend on memory load. *Cortex*, *46*(4), 462-473. https://doi.org/10.1016/j.cortex.2009.11.009.Age

Carlson, S. M., & Meltzoff, A. N. (2008). Bilingual experience and executive functioning in young children. *Developmental Science*, *11*(2), 282-298. https://doi.org/10.1111/j.1467-7687.2008.00675.x.Bilingual

Chertkow, H., Whitehead, V., Phillips, N., Wolfson, C., Atherton, J., & Bergman, H. (2010). Multilingualism (but not always bilingualism) delays the onset of Alzheimer disease: evidence from a bilingual community. *Alzheimer Disease & Associated Disorders*, 24(2), 118-125. https://doi.org/10.1097/WAD.0b013e3181ca1221

Chiswick, B. R., & Miller, P. W. (2005). Linguistic distance: A quantitative measure of the distance between English and other languages. *Journal of Multilingual and Multicultural Development*, *26*(1), 1-11. https://doi.org/10.1080/14790710508668395

Christoffels, I. K., De Groot, A. M., & Kroll, J. F. (2006). Memory and language skills in simultaneous interpreters: The role of expertise and language proficiency. *Journal of Memory and Language*, *54*(3), 324-345. https://doi.org/10.1016/j.jml.2005.12.004

Chung-Fat-Yim, A., Himel, C., & Bialystok, E. (2019). The impact of bilingualism on executive function in adolescents. *International Journal of Bilingualism*, *23*(6), 1278-1290. https://doi.org/10.1177/1367006918781059

Costa, A. (2005). *Lexical access in bilingual production*. Handbook of bilingualism: Psycholinguistic approaches (JF Kroll and AMB de Groot, Ed.) 308–25. Oxford University Press

Craik, F. I., Bialystok, E., & Freedman, M. (2010). Delaying the onset of Alzheimer disease: Bilingualism as a form of cognitive reserve. *Neurology*, 75(19), 1726-1729. https://doi.org/10.1212/WNL.0b013e3181fc2a1c

Czigler, I., & Balázs, L. (2005). Age-related effects of novel visual stimuli in a letter-matching task: an event-related potential study. *Biological Psychology*, *69*(2), 229-242. https://doi.org/10.1016/j.biopsycho.2004.06.006

Daffner, K. R., Chong, H., Sun, X., Tarbi, E. C., Riis, J. L., McGinnis, S. M., & Holcomb, P. J. (2011). Mechanisms underlying age-and performance-related differences in working memory. *Journal of Cognitive Neuroscience*, 23(6), 1298–1314. https://doi.org/10.1162/jocn.2010.21540.Mechanisms

Davis, S.W., Dennis, N. A., Daselaar, S. M., Fleck, M. S., & Cabeza, R. (2007). Que pasa? the posterior–anterior shift in aging. *Cerebral Cortex*, 18(5), 1201–1209. 10.1093/cercor/bhm155.

Dawson, G. D. (1954). A summation technique for the detection of small evoked potentials. *Electroencephalography and Clinical Neurophysiology*, *6*, 65-84.

De Bruin, A., Treccani, B., & Della Sala, S. (2015). Cognitive advantage in bilingualism: An example of publication bias? *Psychological Science*, 26(1), 99-107. https://doi.org/10.1177/0956797614557866

DeLuca, V., Rothman, J., Bialystok, E., & Pliatsikas, C. (2019). Redefining bilingualism as a spectrum of experiences that differentially affects brain structure and function. *Proceedings of the National Academy of Sciences*, *116*(15), 7565-7574. https://doi.org/10.1073/pnas.1811513116

Donchin E (1981) Surprise!… Surprise? *Psychophysiology*, 18, 493–523. https://doi.org/10.1111/j.1469-8986.1981.tb01815.x

Duñabeitia, J. A., Hernández, J. A., Antón, E., Macizo, P., Estévez, A., Fuentes, L. J., & Carreiras, M. (2014). The inhibitory advantage in bilingual children revisited. *Experimental Psychology*. https://doi.org/10.1027/1618-3169/a000243

Ebaid, D., Crewther, S. G., MacCalman, K., Brown, A., & Crewther, D. P. (2017). Cognitive processing speed across the lifespan: beyond the influence of motor speed. *Frontiers in Aging Neuroscience*, 9, 62. https://doi.org/10.3389/fnagi.2017.00062

Eberhard, David M., Gary F. Simons, and Charles D. Fennig (eds.). 2020. Ethnologue: Languages of the World. Twenty-third edition. Dallas, Texas: SIL International. Online version: http://www.ethnologue.com.

Engel de Abreu, P. M. (2011).Working memory in multilingual children: Is there a bilingual effect? *Memory*, *19*(*5*), 529–537. https://doi.org/10.1080/09658211.2011.590504

Engle, R. W., Tuholski, S. W., Laughlin, J. E., & Conway, A. R. (1999). Working memory, short-term memory, and general fluid intelligence: a latent-variable approach. *Journal of Experimental Psychology: General*, *128*(3), 309.

Fejzo, A. (2016). The contribution of morphological awareness to the spelling of morphemes and morphologically complex words in French. *Reading and Writing*, *29*(2), 207-228.

Fernandez, R., Monacelli, A., & Duffy, C. J. (2013). Visual motion event related potentials distinguish aging and Alzheimer's disease. *Journal of Alzheimer's Disease*, *36*(1), 177-183. https://doi.org/10.3233/JAD-122053

Finnigan, S., O'Connell, R.G., Cummins, T.D.R., Broughton, M., Robertson, I.H., 2011. ERP measures indicate both attention and working memory encoding decrements in aging. *Psychophysiology*, 48, 601–611. https://doi.org/10.1111/j.1469-8986.2010.01128.x

Folstein, J.R., Van Petten, C., 2008. Influence of cognitive control and mismatch on the N2 component of the ERP: A review. *Psychophysiology*, 45, 152–170. https://doi.org/10.1111/j.1469-8986.2007.00602.x

Frajzyngier, Z. (2018). Afroasiatic Languages. In Oxford Research Encyclopedia of Linguistics.

Friedman, D., 2012. The components of aging. Oxford Handbok of event-related potential components. Oxford library of psychology. 513–535.

Fujiyama, H., Garry, M. I., Martin, F. H., & Summers, J. J. (2010). An ERP study of age-related differences in the central cost of interlimb coordination. *Psychophysiology*, *47*(3), 501-511. https://doi.org/10.1111/j.1469-8986.2009.00954.x

Gajewski, P. D., & Falkenstein, M. (2014). Age-related effects on ERP and oscillatory EEG-dynamics in a 2-back task. *Journal of Psychophysiology*. doi:10.1027/0269-8803/a000123. https://doi.org/10.1027/0269-8803/a000123

García-Pentón, L., Fernandez Garcia, Y., Costello, B., Duñabeitia, J. A., & Carreiras, M. (2016). The neuroanatomy of bilingualism: how to turn a hazy view into the full picture. *Language, Cognition and Neuroscience*, *31*(3), 303-327. https://doi.org/10.1080/23273798.2015.1068944

Gathercole, V. C. M., Thomas, E. M., Kennedy, I., Prys, C., Young, N., Viñas-Guasch, N., ... & Jones, L. (2014). Does language dominance affect cognitive performance in bilinguals? Lifespan evidence from preschoolers through older adults on card sorting, Simon, and metalinguistic tasks. *Frontiers in Psychology,* 5, 11.

Gevins, A., Smith, M. E., Le, J., Leong, H., Bennett, J., Martin, N., ... & Whitfield, S. (1996). High resolution evoked potential imaging of the cortical dynamics of human working memory. *Electroencephalography and Clinical Neurophysiology,* 98(4), 327-348. https://doi.org/10.1016/0013-4694(96)00288-x

Goh, J. O., & Park, D. C. (2009). Neuroplasticity and cognitive aging: the scaffolding theory of aging and cognition. *Restorative Neurology and Neuroscience,* 27(5), 391-403. https://doi.org/10.3233/RNN-2009-0493

Gold, B. T., Kim, C., Johnson, N. F., Kryscio, R. J., & Smith, C. D. (2013). Lifelong bilingualism maintains neural efficiency for cognitive control in aging. *Journal of Neuroscience,* 33(2), 387-396. https://doi.org/10.1523/JNEUROSCI.3837-12.2013

Grady, C. L., Maisog, J. M., Horwitz, B., Ungerleider, L. G., Mentis, M. J., Salerno, J. A., ... & Haxby, J. V. (1994). Age-related changes in cortical blood flow activation during visual processing of faces and location. *Journal of Neuroscience, 14*(3), 1450-1462.

Green, D. W. (1998). Mental control of the bilingual lexico-semantic system. *Bilingualism: Language and Cognition,* 1(2), 67-81.

Grimes, J.E. and Grimes, B.F. (1993) Ethnologue: Languages of the World (13th edn). Dallas: Summer Institute of Linguistics, Inc.

Grundy JG, Anderson JA and Bialystok E (2017) Bilinguals have more complex EEG brain signals in occipital regions than monolinguals. *NeuroImage,* 159, 280–288. https://doi.org/10.1016/j.neuroimage.2017.07.06

Grundy JG and Timmer K (2017) Bilingualism and working memory capacity: A comprehensive meta-analysis. *Second Language Research,* 33, 325–340. https://doi.org/10.1177/0267658316678286.

Hamdallah, R., 1992. English Word Formation and Its 2.

Harada, C. N., Love, M. C. N., & Triebel, K. L. (2013). Normal cognitive aging. *Clinics in Geriatric Medicine*, *29*(4), 737-752. https://doi.org/10.1016/j.cger.2013.07.002.Normal

Hart-Gonzalez, L. and Lindemann, S. (1993) Expected achievement in speaking proficiency, 1993. School of Language Studies, Foreign Services Institute, Department of State (mimeo).

Hasher, L., & Zacks, R. T. (1988). Working memory, comprehension, and aging: A review and a new view. In G. H. Bower (Ed.), *The Psychology of Learning and Motivation* (Vol. 22, pp. 193–225). San Diego, CA: Academic Press.

Hilchey, M. D., & Klein, R. M. (2011). Are there bilingual advantages on nonlinguistic interference tasks? Implications for the plasticity of executive control processes. *Psychonomic Bulletin & Review*, 18, 625–658. DOI 10.3758/s13423-011-0116-7

Hoffmann, C. (2014). *Introduction to bilingualism*. Routledge.

Hogan, M. J., Kenney, J. P., Roche, R. A., Keane, M. A., Moore, J. L., Kaiser, J., ... & Upton, N. (2012). Behavioural and electrophysiological effects of visual paired associate context manipulations during encoding and recognition in younger adults, older adults and older cognitively declined adults. *Experimental Brain Research*, *216*(4), 621-633. https://doi.org/10.1007/s00221-011-2966-7

Jasper, H.H. (1958). The ten-twenty electrode system of the International Federation. *Electroencephalography and Clinical Neurophysiology, 10*, 371-375.

Kessler, C., & Quinn, M. E. (1987). Language minority children's linguistic and cognitive creativity. *Journal of Multilingual & Multicultural Development*, *8*(1-2), 173-186. https://doi.org/10.1080/01434632.1987.9994284

Kok, A. (2001). On the utility of P3 amplitude as a measure of processing capacity. *Psychophysiology*, 38(3), 557–577. https://doi.org/10.1016/S0167-8760(98)90168-4

Kousaie, S., & Phillips, N. A. (2012a). Conflict monitoring and resolution: Are two languages better than one? Evidence from reaction time and event-related brain potentials. *Brain Research, 1446,* 71–90. https://doi.org/10.1016/j.brainres.2012.01.052

Kousaie, S., & Phillips, N. A. (2012b). Ageing and bilingualism: Absence of a “bilingual advantage” in Stroop interference in a nonimmigrant sample. *The Quarterly Journal of Experimental Psychology*, *65*(2), 356-369. https://doi.org/10.1080/17470218.2011.604788

Kousaie, S., & Phillips, N. A. (2017). A behavioural and electrophysiological investigation of the effect of bilingualism on aging and cognitive control. *Neuropsychologia*, *94*, 23-35.

Kovelman, I., Baker, S. A., & Petitto, L. A. (2008). Age of first bilingual language exposure as a new window into bilingual reading development. *Bilingualism: Language and Cognition*, *11*(2), 203-223. https://doi.org/doi:10.1017/S1366728908003386

Kudo, M., & Swanson, H. L. (2014). Are there advantages for additive bilinguals inworkingmemory tasks? *Learning and Individual Differences, 35,* 96–102. https://doi.org/10.1016/j.lindif.2014.07.019

Li, B. Y., Tang, H. D., & Chen, S. D. (2016). Retrieval deficiency in brain activity of working memory in amnesic mild cognitive impairment patients: A brain event-related potentials study. *Frontiers in Aging Neuroscience*, 8, 54. https://doi.org/10.3389/fnagi.2016.00054

Li, P., Legault, J., & Litcofsky, K. A. (2014). Neuroplasticity as a function of second language learning: anatomical changes in the human brain. *Cortex*, *58*, 301-324. https://doi.org/10.1016/j.cortex.2014.05.001

Lijffijt, M., Lane, S. D., Meier, S. L., Boutros, N. N., Burroughs, S., Steinberg, J. L., … Swann, A. C. (2009). P50, N100, and P200 sensory gating: Relationships with behavioral inhibition, attention, and working memory. *Psychophysiology*, 46(5), 1059–1068. https://doi.org/10.1111/j.1469-8986.2009.00845.x.P50

Lin, M. Y., Gutierrez, P. R., Stone, K. L., Yaffe, K., Ensrud, K. E., Fink, H. A., ... & Mangione, C. M. (2004). Vision impairment and combined vision and hearing impairment predict cognitive and functional decline in older women. *Journal of the American Geriatrics Society*, *52*(12), 1996-2002. https://doi.org/10.1111/j.1532-5415.2004.52554.x

Linck, J.A., Osthus, P., Koeth, J.T., Bunting, M.F., 2014. Working memory and second language comprehension and production: A meta-analysis. *Psychonomic Bulletin & Review*, 21, 861–883. https://doi.org/10.3758/s13423-013-0565-2

López Zunini, R., Morrison, C., Kousaie, S., Taler, V., 2019. Task switching and bilingualism in young and older adults: A behavioral and electrophysiological investigation. *Neuropsychologia*, 133, 107186. https://doi.org/10.1016/j.neuropsychologia.2019.107186

Lorenzo-López, L., Amenedo, E., Pascual-Marqui, R. D., & Cadaveira, F. (2008). Neural correlates of age-related visual search decline: A combined ERP and sLORETA study. *Neuroimage,* 41(2), 511–524. https://doi.org/10.1016/j.neuroimage.2008.02.041

Luck, S. J. (2014). An introduction to the event-related potential technique. Cambridge, MA: The MIT Press.

Luk, G., & Bialystok, E. (2013). Bilingualism is not a categorical variable: Interaction between language proficiency and usage. *Journal of Cognitive Psychology*, 25(5), 605-621. https://doi.org/10.1080/20445911.2013.795574

Luk, G., De Sa, E. R. I. C., & Bialystok, E. (2011). Is there a relation between onset age of bilingualism and enhancement of cognitive control? *Bilingualism: Language and Cognition*, *14*(4), 588-595. https://doi.org/10.1017/S1366728911000010

Lukasik, K. M., Lehtonen, M., Soveri, A., Waris, O., Jylkkä, J., & Laine, M. (2018). Bilingualism and working memory performance: Evidence from a large-scale online study. *PloS one*, *13*(11).

Luo, L., & Craik, F. I. (2008). Aging and memory: A cognitive approach. *The Canadian Journal of Psychiatry*, 53(6), 346-353.

Maldonado García, MI, & Borges de Souza, AM (2014). Lexical similarity level between English and Portuguese. ELIA, 14, 145-163. https://doi.org/10.12795/elia.2014.i14.06

Maletina, O. V. (2014). Understanding L1-L2 Fluency relationship across different languages and different proficiency levels (Masters dissertation). Brigham Young University, Provo, Utah.

Mamiya, P. C., Richards, T. L., Coe, B. P., Eichler, E. E., & Kuhl, P. K. (2016). Brain white matter structure and COMT gene are linked to second-language learning in adults. *Proceedings of the National Academy of Sciences*, *113*(26), 7249-7254. https://doi.org/10.1073/pnas.1606602113

Mårtensson, J., Eriksson, J., Bodammer, N. C., Lindgren, M., Johansson, M., Nyberg, L., & Lövdén, M. (2012). Growth of language-related brain areas after foreign language learning. *NeuroImage*, *63*(1), 240-244. https://doi.org/10.1016/j.neuroimage.2012.06.043

McEvoy, L. K., Pellouchoud, E., Smith, M. E., & Gevins, A. (2001). Neurophysiological signals of working memory in normal aging. *Cognitive Brain Research*, 11(3), 363–376. https://doi.org/10.1016/S0926-6410(01)00009-X

Mertens, R., & Polich, J. (1997). P300 from a single stimulus paradigm: passive versus active tasks and stimulus modality. E*lectroencephalography and Clinical Neurophysiology/Evoked Potentials Section*, *104*(*6*), 488–497. https://doi.org/10.1016/S0168-5597(97)00041-5

Milham, M. P., Erickson, K. I., Banich, M. T., Kramer, A. F., Webb, A., Wszalek, T., & Cohen, N. J. (2002). Attentional control in the aging brain: insights from an fMRI study of the stroop task. *Brain and Cognition*, *49*(3), 277-296. https://doi.org/10.1006/brcg.2001.1501

Missonnier, P., Gold, G., Leonards, U., Costa-Fazio, L., Michel, J. P., Ibáñez, V., & Giannakopoulos, P. (2004). Aging and workingmemory: Early deficits in EEG activation of posterior cortical areas. *Journal of Neural Transmission*, 111(9), 1141–1154. https://doi.org/10.1007/s00702-004-0159-2

MØLLER, Hermann. 1879. Rewiew of F. KLUGE, Beiträge zur Geschichte der germanischen Conjugation. *Englische Studien,* 3: 148–164

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

Moreno, S., Wodniecka, Z., Tays, W., Alain, C., & Bialystok, E. (2014). Inhibitory control in bilinguals and musicians: event related potential (ERP) evidence for experience-specific effects. *PloS One*, *9*(4). https://doi.org/10.1371/journal.pone.0094169

Morrison, C., Kamal, F., & Taler, V. (2019). The influence of working memory performance on event-related potentials in young and older adults. *Cognitive Neuroscience*, *10*(3), 117-128. https://doi.org/10.1080/17588928.2019.1570104

Myerson, J., Emery, L., White, D. A., & Hale, S. (2003). Effects of age, domain, and processing demands on memory span: Evidence for differential decline. *Aging, Neuropsychology, and Cognition*, *10*(1), 20-27. https://doi.org/10.1076/anec.10.1.20.13454

Nichols, E.S., Joanisse, M.F., (2016). Functional activity and white matter microstructure reveal the independent effects of age of acquisition and proficiency on second-language learning. *Neuroimage,* 143, 15–25. https://doi.org/10.1016/j.neuroimage.2016.08.053

Nichols, E. S., Wild, C. J., Stojanoski, B., Battista, M. E., & Owen, A. M. (2020). Bilingualism Affords No General Cognitive Advantages: A Population Study of Executive Function in 11,000 People. *Psychological Science,* 0956797620903113. https://doi.org/10.1177/0956797620903113

Nilsson, L. G. (2003). Memory function in normal aging. *Acta Neurologica Scandinavica*, *107*, 7-13.

Obeid, N., (2009). Semitic Languages. *Etymological Study of Semitic Languages (Arabic and Hebrew)* (pp. 10-27)

O'Connell, R. G., Balsters, J. H., Kilcullen, S. M., Campbell, W., Bokde, A. W., Lai, R., … Robertson, I. H. (2012). A simultaneous ERP/fMRI investigation of the P300 aging effect. *Neurobiology of Aging*, 33(10), 2448–2461.

Paap, K. R., & Greenberg, Z. I. (2013). There is no coherent evidence for a bilingual advantage in executive processing. *Cognitive Psychology*, *66*(2), 232-258. https://doi.org/10.1016/j.cogpsych.2012.12.002

Padgaonkar, N. A., Zanto, T. P., Bollinger, J., & Gazzaley, A. (2017). Predictive cues and age-related declines in working memory performance. *Neurobiology of Aging, 49*, 31-39. https://doi.org/10.1016/j.neurobiolaging.2016.09.002

Park, D. C., Lautenschlager, G., Hedden, T., Davidson, N. S., Smith, A. D., & Smith, P. K. (2002). Models of visuospatial and verbal memory across the adult life span. *Psychology and Aging*, *17*(2), 299. https://doi.org/10.1037/0882-7974.17.2.299

Park, D. C., & Reuter-Lorenz, P. (2009). The adaptive brain: aging and neurocognitive scaffolding. *Annual review of Psychology*, 60, 173-196. https://doi.org/10.1146/annurev.psych.59.103006.093656

Patel, S. H., & Azzam, P. N. (2005). Characterization of N200 and P300: Selected studies of the event-related potential. *International Journal of Medical Sciences*, 2(4), 147. https://doi.org/10.1016/j.neurobiolaging.2011.12.021\

Peal, E., & Lambert, W. E. (1962). The relation of bilingualism to intelligence. *Psychological Monographs: General and Applied*, *76*(*27*), 1.

Pekkonen, E., Rinne, T., Reinikainen, K., Kujala, T., Alho, K., & Naatanen, R. (1996). Aging effects on auditory processing: an event-related potential study. *Experimental Aging Research*, *22*(2), 171-184. https://doi.org/10.1080/03610739608254005

Perani, D., & Abutalebi, J. (2015). Bilingualism, dementia, cognitive and neural reserve. *Current Opinion in Neurology*, 28(6), 618-625.

Picton, T. W. (1992). The P300 wave of the human event-related potential. *Journal of Clinical Neurophysiology*, *9*(4), 456-479. https://doi.org/10.1097/00004691-199210000-00002

Picton, T. W., Lins, O. G., & Scherg, M. (1995). The recording and analysis of event-related potentials. *Handbook of Neuropsychology*, *10*.

Pinal D, Zurrón M and Díaz F (2014) Effects of load and maintenance duration on the time course of information encoding and retrieval in working memory: from perceptual analysis to post-categorization processes. *Frontiers in Human Neuroscience*. https://doi.org/10.3389/fnhum.2014.00165

Pivik, R. T., Broughton, R. J., Coppola, R., Davidson, R. J., Fox, N., & Nuwer, M. R. (1993). Guidelines for the recording and quantitative analysis of electroencephalographic activity in research contexts. *Psychophysiology*, 30(6), 547-558.

Pliatsikas, C., DeLuca, V., Moschopoulou, E., & Saddy, J. D. (2017). Immersive bilingualism reshapes the core of the brain. *Brain Structure and Function, 222*(4), 1785-1795. https://doi.org/10.1007/s00429-016-1307-9

Plomin, R., Haworth, C. M., Meaburn, E. L., Price, T. S., Wellcome Trust Case Control Consortium 2, & Davis, O. S. (2013). Common DNA markers can account for more than half of the genetic influence on cognitive abilities. *Psychological Science*, 24(4), 562-568. https://doi.org/10.1177/0956797612457952

Polich, J. (1996). Meta-analysis of P300 normative aging studies. *Psychophysiology*, *33*(*4*), 334–353.

Polich, J. (2007). Updating P300: An integrative theory of P3a and P3b. Clinical *Neurophysiology*, 118(10), 2128–2148. https://doi.org/10.1016/j.clinph.2007.04.019

Prior, A., & MacWhinney, B. (2010). A bilingual advantage in task switching. *Bilingualism: Language and Cognition*, 13(2), 253-262. https://doi.org/10.1017/s1366728909990526

Prior, A., & Gollan, T. H. (2011). Good language-switchers are good task-switchers: Evidence from Spanish–English and Mandarin–English bilinguals. *Journal of the International Neuropsychological Society, 17*(*4*), 682–691. https://doi.org/10.1017/S1355617711000580

Ratiu, I., & Azuma, T. (2014). Working memory capacity: Is there a bilingual advantage? *Journal of Cognitive Psychology*, *27*(*1*), 1–11. https://doi.org/10.1080/20445911.2014.976226

Reuter-Lorenz, P. A., & Lustig, C. (2005). Brain aging: reorganizing discoveries about the aging mind. *Current Opinion in Neurobiology*, 15(2), 245-251. https://doi.org/10.1016/j.conb.2005.03.016

Reuter-Lorenz, P. A., & Cappell, K. A. (2008). Neurocognitive aging and the compensation hypothesis. *Current Directions in Psychological Science*, 17(3), 177–182. https://doi.org/10.1111/j.1467-8721.2008.00570.x

Rey-Mermet, A., & Gade, M. (2018). Inhibition in aging: What is preserved? What declines? A meta-analysis. *Psychonomic Bulletin & Review*, 25(5), 1695-1716. https://doi.org/10.3758/s13423-017-1384-7

Riis, J. L., Chong, H., McGinnnis, S., Tarbi, E., Sun, X., Holcomb, P. J., ... & Daffner, K. R. (2009). Age-related changes in early novelty processing as measured by ERPs. *Biological Psychology*, *82*(1), 33-44. https://doi.org/10.1038/jid.2014.371

Rosselli, M., Ardila, A., Santisi, M. N., Arecco, M. D. R., Salvatierra, J., Conde, A., & Lenis, B. O. N. I. E. (2002). Stroop effect in Spanish–English bilinguals. *Journal of the International Neuropsychological Society*, *8*(6), 819-827. https://doi.org/10.1017/S1355617702860106

Rossi, E., Cheng, H., Kroll, J. F., Diaz, M. T., & Newman, S. D. (2017). Changes in white-matter connectivity in late second language learners: Evidence from diffusion tensor imaging. *Frontiers in Psychology*, *8*, 2040. https://doi.org/10.3389/fpsyg.2017.02040

Rowe, Bruce M.; Levine, Diane P. (2015). *A Concise Introduction to Linguistics*. Routledge. pp. 340–341. ISBN 1317349288.

Rydine, K. (2014) Arabic: A Linguistic Introduction. Cambridge: Cambridge University Press. doi:10.1017/CBO9781139151016

Saliasi, E., Geerligs, L., Lorist, M. M., & Maurits, N. M. (2013). The relationship between P3 amplitude and working memory performance differs in young and older adults. *PLoS One*, 8 (5). doi:10.1371/journal.pone.0063701

Salthouse, T. A. (1996). The processing-speed theory of adult age differences in cognition. *Psychological Review*, 103(3), 403. ttps://doi.org/10.1037/0033-295X.103.3.403

Salthouse, T. A., & Ferrer-Caja, E. (2003). What needs to be explained to account for age-related effects on multiple cognitive variables? *Psychology and Aging*, 18(1), 91. https://doi.org/10.1037/0882-7974.18.1.91

Salthouse, T. A. (2009). Decomposing age correlations on neuropsychological and cognitive variables. *Journal of the International Neuropsychological Society*, *15*(5), 650-661. https://doi.org/10.1017/S1355617709990385

Schaie, K. W. (1996). *Intellectual development in adulthood: The Seattle longitudinal study*. Cambridge University Press.

Schweizer, T. A., Ware, J., Fischer, C. E., Craik, F. I., & Bialystok, E. (2012). Bilingualism as a contributor to cognitive reserve: Evidence from brain atrophy in Alzheimer's Disease. *Cortex*, *48*(8), 991-996. https://doi.org/10.1016/j.cortex.2011.04.009

Segalowitz, N., & Frenkiel-Fishman, S. (2005). Attention control and ability level in a complex cognitive skill: Attention shifting and second-language proficiency. *Memory & Cognition*, 33(4), 644-653. https://doi.org/10.3758/BF03195331

Service, E. (1992). Phonology, working memory, and foreign-language learning. *The Quarterly Journal of Experimental Psychology Section A*, *45*(1), 21-50. https://doi.org/10.1080/14640749208401314

Singh-Manoux, A., Kivimaki, M., Glymour, M.M., Elbaz, A., Berr, C., Ebmeier, K.P., Ferrie, J.E., Dugravot, A., 2012. Timing of onset of cognitive decline: results from Whitehall II prospective cohort study. *Bmj*, 344, d7622–d7622. https://doi.org/10.1136/bmj.d7622

Soliman, A. M. (2014). Bilingual advantages of working memory revisited: A latent variable examination. *Learning and Individual Differences*, *32*, 168-177. https://doi.org/10.1016/j.lindif.2014.02.005

Stern, Y., Moeller, J.R., Anderson, K.E., Luber, B., Zubin, N.R., DiMauro, A.A., Park, A., Campbell, C.E., Marder, K., Bell, K., Van Heertum, R., Sackeim, H.A., (2000). Different brain networks mediate task performance in normal aging and AD: Defining compensation. *Neurology*, 55, 1291–1297. https://doi.org/10.1212/WNL.55.9.1291

Stern, Y. (2002). What is cognitive reserve? Theory and research application of the reserve concept. *Journal of the international Neuropsychological Society*, 8(3), 448-460. https://doi.org/10.1017/S1355617702813248

Stern, Y., 2009. Cognitive reserve. *Neuropsychologia*, 47, 2015–2028. https://doi.org/10.1016/j.neuropsychologia.2009.03.004

Sullivan, M. D., Janus, M., Moreno, S., Astheimer, L., & Bialystok, E. (2014). Early stage second-language learning improves executive control: Evidence from ERP. *Brain and Language*, *139*, 84-98. https://doi.org/10.1016/j.bandl.2014.10.004

Sullivan, M. D., Prescott, Y., Goldberg, D., & Bialystok, E. (2016). Executive control processes in verbal and nonverbal working memory: The role of aging and bilingualism. *Linguistic Approaches to Bilingualism*, *6*(1-2), 147-170. https://doi.org/10.1075/lab.15056.sul

Sutton, S., Braren, M., Zubin, J., & John, E. R. (1965). Evoked-potential correlates of stimulus uncertainty. *Science*, *150*(3700), 1187-1188. https://doi.org/10.1126/science.150.3700.1187

Tao, L., Marzecová, A., Taft, M., Asanowicz, D., & Wodniecka, Z. (2011). The efficiency of attentional networks in early and late bilinguals: the role of age of acquisition. *Frontiers in Psychology*, *2*, 123. https://doi.org/10.3389/fpsyg.2011.00123

Vallesi, A. (2011). Targets and non-targets in the aging brain: a go/nogo event-related potential study. *Neuroscience Letters*, *487*(3), 313-317. https://doi.org/10.1016/j.neulet.2010.10.046

Versteegh, K. (2014). *Arabic language*. Edinburgh University Press.

von Moltke, L. L., Greenblatt, D. J., Romach, M. K., & Sellers, E. M. (2001). Cognitive toxicity of drugs used in the elderly. *Dialogues in Clinical Neuroscience*, *3*(3), 181.

Walter, W. G., Cooper, R., Aldridge, V. J., McCallum, W. C., & Winter, A. L. (1964). Contingent negative variation: an electric sign of sensori-motor association and expectancy in the human brain. *Nature*, *203*(4943), 380-384.

World Health Organization (2015) *World Report on Ageing and Health*. ISBN 978 92 4 069479 8 (ePub). WHO Press, Switzerland

Whitford, V., & Titone, D. (2012). Second-language experience modulates first-and second-language word frequency effects: Evidence from eye movement measures of natural paragraph reading. *Psychonomic Bulletin & Review*, *19*(1), 73-80. https://doi.org/10.3758/s13423-011-0179-5

Wingfield, A., Stine-Morrow, E.A.L., 2000. Language and speech, in: Salthouse, T.A., Craik, F.I.M. (Eds.), The Handbook of Aging and Cognition. Mahwah, NJ: Erlbaum, pp. 359–416.

Wild-Wall, N., Falkenstein, M., & Gajewski, P. D. (2011). Age-related differences in working memory performance in a 2-back task. *Frontiers in Psychology*, 2, 186. doi:10.3389/ fpsyg.2011.00186

Wu, Y. J., & Thierry, G. (2013). Fast modulation of executive function by language context in bilinguals. *Journal of Neuroscience*, 33(33), 13533-13537. https://doi.org/10.1523/JNEUROSCI.4760-12.2013

Yamasaki, T., Goto, Y., Ohyagi, Y., Monji, A., Munetsuna, S., Minohara, M., ... & Tobimatsu, S. (2012). Selective impairment of optic flow perception in amnestic mild cognitive impairment: evidence from event-related potentials. *Journal of Alzheimer's Disease*, *28*(3), 695-708.

Part 1: Paradigm 1 (Study 1)

Study 1 was published in Bilingualism: Language and Cognition and is formatted in accordance with the requirements of that journal.

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This study was designed to examine if ERP differences are present between young adult monolinguals and bilinguals. While previous research has examined the effects of bilingualism on working memory, no studies have investigated whether working memory differs between monolinguals and bilinguals using ERPs. ERPs should provide a more precise understanding than performance measures as to whether cognitive processing differs between bilinguals and monolinguals. The n-back task was employed while EEG, reaction time, and accuracy was recorded in younger adult English monolinguals and English-French bilinguals.

Paradigm 1 (Study 1): The influence of bilingualism on working memory event-related potentials

Short title: Bilingualism and working memory
Full title: The influence of bilingualism on working memory event-related potentials

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Abstract

Bilingualism has been found to enhance the ability to store and manipulate information in working memory (WM). However, previous studies of WM function in bilingualism have been limited to behavioral measures, leaving questions unanswered regarding the effects of bilingualism on neural mechanisms employed during WM tasks. We recorded brain activity (event-related potentials; ERPs) while participants (23 English-speaking and 21 English-French bilingual) performed an n-back WM task. Accuracy and reaction time were similar across groups, but monolinguals exhibited smaller P300 amplitudes relative to bilinguals, suggesting that bilinguals have more cognitive resources available to complete cognitively demanding tasks.

Keywords: bilingualism, event-related potentials, working memory

1. Introduction

As early as the 1960s, research suggested that bilinguals may experience cognitive advantages over monolinguals, particularly in tasks involving problem solving and creativity (Bain, 1975; Kessler et al., 1987; Peal & Lambert, 1962). However, recent research examining this bilingual advantage has yielded mixed findings, with some studies finding improved executive function (EF) in bilinguals (Badzakova-Trajkov, 2008; Bialystok, Craik, Klein, & Viswanathan, 2004; Bialystok & Martin, 2004; Prior & Gollan, 2011), and others finding no such advantage (Duñabeitia et al., 2013; Gathercole et al., 2014; Goldman et al., 2014).

While many previous studies have examined EF differences in bilingualism, few have studied working memory (WM) differences. WM, is involved with temporarily storing and manipulating information that is no longer perceptually present (Baddeley, 2003; Diamond, 2012). Similar to EF studies, current findings have reported mixed results with respect to the effect of bilingualism on WM performance, with some reporting improved performance in bilinguals relative to monolinguals (Kudo & Swanson, 2014; Morales et al., 2013), and others finding no cognitive advantage (Bialystok, 2009; Blom et al., 2014; Bonifacci & Giombini, 2011; Engel de Abreu & Abreu, 2011; Ratiu & Azuma, 2015). The present study aimed to determine whether WM differences between monolinguals and bilinguals are measurable through brain activity patterns (event-related potentials; ERPs).

Electroencephalography (EEG) is a technique that can be combined with cognitive, sensory, or motor tasks, to extract waveforms reflecting the brain's activity during specific mental processes (Luck, 2014). These waveforms, referred to as event-related potentials (ERPs), are associated with varying cognitive processes, and can be measured through latency (time to process the stimulus) and amplitude (intensity of the response) (Luck, 2014).

Each component may be positive or negative, and has a typical latency range; for example, the P300 is a positive-going component occurring around 300ms after stimulus onset.

The components of interest in the current study are the P200, N200 and P300. The P200 normally occurs 150-300ms following stimulus presentation (Luck, 2014), and is thought to be associated with WM (Finnigan et al., 2011; Lijffijt et al., 2009), with smaller amplitudes representing lower WM performance (Finnigan et al., 2011). The N200 occurs 200-350ms post-stimulus presentation (Folstein & Van Petten, 2008) and reflects pre-attention and the ability to discriminate an incongruity between a current stimulus and the representation of a stimulus held in memory (Bennys et al., 2007; Folstein & Van Petten, 2008; Patel & Azzam, 2005). The N200 occurs later in low performers, suggesting impairments in the processing of stimulus detection (Daffner et al., 2011). The P300 occurs 300-600ms post-stimulus and is involved with many cognitive processes such as cognitive control, attention, and memory processing (Mertens & Polich, 1997; Polich, 2007). The P300 can be divided into two subcomponents, the frontally maximal P3a and the parietally maximal P3b. The P3a, which occurs earlier than the P3b, is elicited only when the participant is not actively attending to a stimulus (response to a non-target stimulus), whereas the P3b requires active attention and detection of a target (Luck, 2014; Polich, 2007). P300 latency reflects information processing speed, and increases as processing time increases (Kok, 2001; Polich, 1996), while P300 amplitude reflects intensity of processing (Kok, 2001) and resource allocation (Polich, 1996).

WM can be studied employing the n-back task, where participants are required to determine whether a current stimulus matches a stimulus from *n*-steps earlier. Previous research on the n-back task has shown that as WM load increases, the P300 decreases due to diminished WM capacity and fewer available resources to complete the task (Daffner et al., 2011; Gevins et al., 1996). However, high performers exhibit increased P300s, as task difficulty increases due to the availability of more resources to allocate to task completion (Daffner et al., 2011).

ERP studies of executive control have found differences between monolinguals and bilinguals across a range of tasks. Barac and colleagues found that bilingual children exhibited larger amplitudes, shorter latencies, and better behavioral performance to complex response inhibition (Barac et al., 2016; Grundy et al., 2017; Kousaie & Phillips, 2012b) compared to monolinguals, indicating improved executive control in bilinguals. Electrophysiological differences between monolinguals and bilinguals have also been found in both cognitive monitoring and task switching (Barac et al., 2016; Grundy et al., 2017; Kousaie & Phillips, 2012b), although in the latter two studies no behavioral differences were observed. These findings indicate that ERPs may offer additional insight into the difference in cognitive processing between monolinguals and bilinguals.

The present study aimed to examine the effect of bilingualism on WM. Monolingual and bilingual participants completed the n-back WM task while EEG was recorded. We expected bilinguals to have shorter RTs and improved accuracy, with larger P200s, reflecting improved WM performance and capacity. We also hypothesized that bilinguals would have smaller N200 amplitudes than monolinguals, reflecting heightened ability to discriminate between a current stimulus and the one held in memory. With respect to the P300[i], both monolinguals and bilinguals were expected to exhibit the typical amplitude reduction with increased WM load. Bilinguals were expected to have larger P300 amplitudes than monolinguals overall, reflecting higher WM capacity and enhanced ability to allocate their resources to complete the task.

2. Methods

2.1 ***Participants***

Fifty young adults between 18 and 30 were recruited through word of mouth at the University of Ottawa. Of the fifty participants recruited, six were excluded for the following reasons: two scored less than 50% during the 2-back, two revealed after testing that they were fluent in a third language, and ERP data of two participants was very noisy, requiring exclusion of more than 25% of their trials. There were 23 English monolinguals (17 females) and 21 bilinguals (15 females) totaling forty-four participants remaining. The monolingual group had a mean age of 19.70(±2.32) and 14.61(±1.83) years of education, while the bilingual group had a mean age of 19.71(±1.65) and 14.71 (±1.52) years of education. Groups did not significantly differ in age or education (Table 1). Bilingual participants were native English speakers and highly proficient in French; all became proficient in French before the age of 13. Demographic information and neuropsychological test scores are provided in Table 1. 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.

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

	Group		t-test and *p*-values
	Monolingual	Bilingual	
N (females)	23(17 females)	21(15 females)	
Age	19.70(2.32)	19.71(1.65)	t(42)= - 0.03, *p*=0.98
Education	14.61(1.83)	14.71(1.52)	t(42)= -0.20, *p*=0.84
Digit Span Forward	11.22(2.19)	11.47(2.48)	t(42)= -0.37, *p*=0.72
Digit Span Backward	7.13(1.98)	7.57(2.29)	t(42)= -0.68, *p*=0.50
Letter # Sequencing	11.34(2.08)	12.23(3.16)	t(42)= -1.11, *p*=0.27
WCST	4.30(0.97)	4.52(0.98)	t(42)= -0.74, *p*=0.46
Stroop1	112.57(5.10)	111.81(16.39)	t(42)= 0.17, *p*=0.87
Stroop2	80.91(7.89)	79.62(10.68)	t(42)= 0.46, *p*=0.65
Stroop3	52.35(11.75)	54.52(10.75)	t(42)= -0.64, *p*=0.53
Digit Symbol-Written	66.39(12.54)	64.52(12.23)	t(42)= -0.74, *p*=0.62
Digit Symbol-Oral	71.17(11.88)	73.29 (15.60)	t(42)= 0.50, *p*=0.61
BNT-English (/60)	53.21(4.06)	50.38(8.27)	t(42)= 0.37, *p*=0.71
F Fluency- English	13.09(4.36)	13.61(4.25)	t(42)= -0.41, *p*=0.68
A Fluency- English	11.74(2.85)	12.00(5.13)	t(42)= -0.21, *p*=0.83
S Fluency- English	16.30(5.10)	15.19(5.18)	t(42)= 0.72, *p*=0.47
F Fluency- French		8.90(4.18)	
A Fluency- French		9.67(4.41)	
S Fluency- French		8.29(3.45)	
BNT-French (/60)		35.43(11.36)	

Notes: BNT = Boston Naming Test, WCST= Wisconsin Card Sorting Test. Stroop1= requires participants to read name of colors, Stroop2=read the color of "X's", 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.

Participants completed a self-rated language proficiency scale for English and French, and bilinguals completed a language history and usage questionnaire to assess frequency of language use in different contexts (Table 2). If participants reported knowledge of another language rated above a 2 (“very little ability”) they were excluded. Participants had no neurological or psychiatric history, were not taking medications that influence the central nervous system, and had not suffered any major head injuries.

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

	Monolinguals	Bilinguals
French Age of Aqusition	6.13(1.54)	4.05(2.27)
French Age of Fluency	----	9.95(3.28)
English Proficency Rating		
Listening	4.87(0.34)	5(0)
Reading	5(0)	5(0)
Speaking	5(0)	5(0)
Writing	4.96(0.21)	4.95(0.22)
French Proficency Rating		
Listening	1.94(0.24)	4.48(0.51)
Reading	1.88(0.49)	4.33(0.48)
Speaking	1.82(0.39)	4.14(0.48)
Writing	1.71(0.47)	3.76(0.70)
French use at home		
Speaking	----	28.57%(37.32)
Listening to speak	----	33.33% (32.91)
Reading	----	25% (32.60)
Writing	----	21.43% (31.90)
French use at school/work:		
Speaking	----	34.52% (25.59)
Listening to speak	----	40.47% (24.34)
Reading	----	29.76% (23.21)
Writing	----	32.14% (25.18)

Note: self rated profiency 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 abilties. Language use was rated on a 5 point scale: 0%, 25%, 50%, 75%, and 100% of the time.

2.2 ***Procedure***

Participants completed a neuropsychological battery that included letter/number sequencing, forward and backward digit span (Wechsler Memory Scale, (Wechsler, 1997)), the Wisconsin card sorting test (WCST) (Grant & Berg, 1948), both the written and verbal Digit Symbol Substitution subtest of the Wechsler Adult Intelligence Scale-III (WAIS-III) (Wechsler, 1997), the Stroop task (Stroop, 1935), some verbal fluency tests (FAS, animal fluency) and the Boston Naming Test (BNT) (Kaplan, Goodglass, & Weintraub, 1983). Bilinguals completed the fluency and BNT in both English and French to allow characterization of their language abilities in both languages.

Neuropsychological data were collected in one testing session. In a second testing session, participants completed the n-back task (and another task not reported in this paper)[ii] while EEG was recorded. Each session lasted approximately 1.5 to 2 hours.

2.3 ***N-back working memory task***

Participants saw digits one at a time at the center of a computer screen for 1000ms with an inter-stimulus interval of 1700ms. The n-back task includes three different memory load conditions. In the 0-back condition, participants will press the mouse key in response to the number 0, in the 1-back condition participants will press the mouse key when the number matches the previous number seen (e.g. a 9 and then another 9), and in the 2-back condition participants will press the mouse key when the digit matches the one presented two trials previously (e.g. a 9 followed by a 6 and then another 9). Each condition consists of 180 trials, with 60 requiring the participant to respond (by pressing the mouse key). Each condition lasted approximately 10 minutes, for a total of 30 minutes.

2.4 ***EEG data recording and analysis***

The EEG was recorded from 32 active silver-silver chloride electrodes attached to an electrode cap (Brain Products, GmbH, Munich, Germany) placed according to the international 10-20 system. An EOG electrode was placed on the infraorbital ridge of the left eye to record vertical eye movements. An average of the mastoids was used as a reference for all channels. Inter-electrode impedances varied from 0-20kΩ and the EEG was digitized at rate of 500Hz.

EEG data was processed offline using Brain Vision Analyser 2.1 (Brain Products, GmbH, Munich, Germany). The EEG was down-sampled to 250Hz with a time constant of 2s, and digitally filtered using a low pass filter of 30Hz. The EEG was visually inspected for channels containing high levels of noise, and high noise channels were replaced by interpolating the data of surrounding electrode sites (Perrin et al., 1989). Independent Components Analysis was used to identify eye movements and blinks that were independent of the EEG activity. The continuous EEG was reconstructed into 1200ms epochs starting 200ms before stimulus onset. The 200ms pre-stimulus period served as a zero-voltage baseline period, and epochs were baseline-corrected. Any epochs containing EEG activity exceeding ±100μV were rejected from the averaging, with correct trials for both target and non-target trials included in averages.

3. Statistical analysis and results

3.1 ***Neuropsychological data***

Neuropsychological test scores from monolingual and bilingual groups were compared using independent sample t-tests, with Bonferroni correction for multiple comparisons. There were no significant differences between monolinguals and bilinguals on any of the neuropsychological test scores. Bilingual participants' verbal fluency task performance in

English and French was compared using a repeated-measures ANOVA. Their performance was better in English than French on all measures except F fluency, indicating that our bilingual participants were English-dominant.

3.2 ***N-back behavioral performance***

Trials with RTs exceeding ±2.5 standard deviations from the mean by participant and condition were excluded as outliers. Accuracy and RT were analyzed with two separate 3x2 mixed ANOVAs with Condition (0-,1- and 2-back) as a within-subject factor and Group (Monolingual vs Bilingual) as a between-subject factor. Outliers constituted less than 1% of the trials in all conditions and groups. Average accuracy and RTs by group are shown in Table 3.

Table 3: Behavioral performance on the n-back task for each condition and group.

Measures for N-back Mean (Standard Deviation)	Group		t-test and *p*-values
	Monolinguals (n=23)	Bilinguals (n=21)	
0-back			
RT(ms)	391.02(41.04)	382.32(56.40)	t(42)=0.59, *p*=.56
Accuracy to Targets	97.30(1.57)	96.98(1.86)	t(42)=0.63, *p*=.53
Omission Errors (%)	0.13(0.46)	0.14(0.48)	t(42)= -0.88, *p*=.93
Commission errors (%)	0.35(0.57)	0.19(0.57)	t(42)=0.96, *p*=.34
Outliers	1.48(0.85)	1.67(0.91)	t(42)=-0.71, *p*=.48
1-back			
RT(ms)	456.96(60.05)	455.28(82.25)	t(42)=.09, *p*=.93
Accuracy to Targets	91.23(9.40)	93.17(5.70)	t(42)= -0.70, *p*=.48
Omission Errors (%)	3.96(5.94)	2.76(3.70)	t(42)=0.79, *p*=.43
Commission errors (%)	0.39(0.67)	1.00(1.38)	t(42)= -1.84, *p*=.08
Outliers	1.30(0.93)	1.33(0.91)	t(42)=-1.04, *p*=.92
2-back			
RT(ms)	500.67(58.79)	471.15(73.54)	t(42)= 1.49, *p*=.14
Accuracy to Targets	68.84(18.38)	74.68(10.89)	t(42)= -1.26 *p*=.20
Omission Errors (%)	18.17(11.01)	13.90(7.01)	t(42)=1.52, *p*=.13
Commission errors (%)	6.48(3.09)	6.05(2.46)	t(42)=0.51, *p*=.61
Outliers (#)	0.52(0.67)	1.28(1.06)	t(42)=-2.90, *p*=.006*

Notes: The differences between groups only showed monolinguals having fewer outliers in the 2-back condition. However, when a repeated measures ANOVA was conducted the difference was not significan.

A repeated-measures ANOVA revealed decreasing accuracy with increasing task difficulty overall (main effect of Condition F (2, 84) =113.22, p<0.001, $n_p{}^2$= 0.73). No other effects reached significance (Group: F (1,42) =1.24, p=0.271**,** Condition X Group: F (2, 84) =1.44, p=0.244). Similarly, longer RTs were observed as task difficulty increased (main effect of Condition F (2, 84) =63.98, p<0.001, $n_p{}^2$ = 0.60), but no other effects reached significance (Group: F (1,42) =.72, p=0.402, Condition X Group: F (2,84) =1.33, p=0.268).

3.3 ***ERP analyses***

Three components were selected for analysis: the P200, N200, and P300. For all three components, four midline sites were chosen for analysis (Fz, FCz, Cz, and Pz). A Greenhouse-Geisser correction procedure was used for all ERP analyses when sphericity was violated (Greenhouse & Geisser, 1959). Bonferroni-corrected pairwise comparisons were performed when comparing groups at the four sites of measurement.

The P200 was scored as the most positive peak from 100-200 ms and the N200 was scored as the most negative peak from 200-350 ms. Two separate 4x3x2 mixed ANOVAs (one for latency and one for amplitude) were conducted with the within-subject factors Site (Fz, FCz, Cz, and Pz) and Condition (0-,1-,2-back), and the between-subject factor of Group (monolingual vs. bilingual) for both the P200 and N200. Visual inspection of the P300 showed no distinctive peak in either the monolingual or bilingual group. Thus, mean amplitudes were calculated at all midline regions with a time window of 300-500 ms. One 4x3x2 mixed ANOVA was conducted for mean amplitude analysis, with the within-subject factors of Site (Fz, FCz, Cz, and Pz) and Condition (0-,1-,2-back), and the between-subject factor of Group (monolingual vs. bilingual).

P200 latency analysis revealed a main effect of Condition, F (2, 84) =7.99, p=0.003, n_p^2 =0.16, with post hoc comparison indicating that the 0-back had a shorter latency (166.05ms) than the 1-back (174.67 ms, p=0.006) and 2-back (172.86 ms, p=0.035) conditions, which did not differ from each other (Figure 1). P200 amplitude analysis revealed a main effect of Condition, F (3,126) = 8.19, p=0.001, n_p^2 =0.16, with post hoc tests revealing smaller peak amplitudes for the 0-back (5.56 μV, p=0.002,) and 1-back (5.75 μV, p=0.010) conditions compared to the 2-back condition (6.39 μV). No effects of Group (monolingual versus bilingual) nor other effects of interest were found (Figure 2).

N200 latency analysis revealed no significant main effects or interactions (all *p's>0.05)*. Significant differences in N200 amplitude were observed: a main effect of Condition F (2, 84) =24.09, p <0.001 n_p^2 =0.36 was due to larger amplitudes in the 0-back condition (-3.10 μV) compared to the 1-back (-2.09 μV) and 2-back (-1.44 μV), p <0.001, and a larger amplitude in the 1-back compared to the 2-back (p=0.006). That is, the amplitude became less negative (smaller) as task difficulty increased (Figure 1).

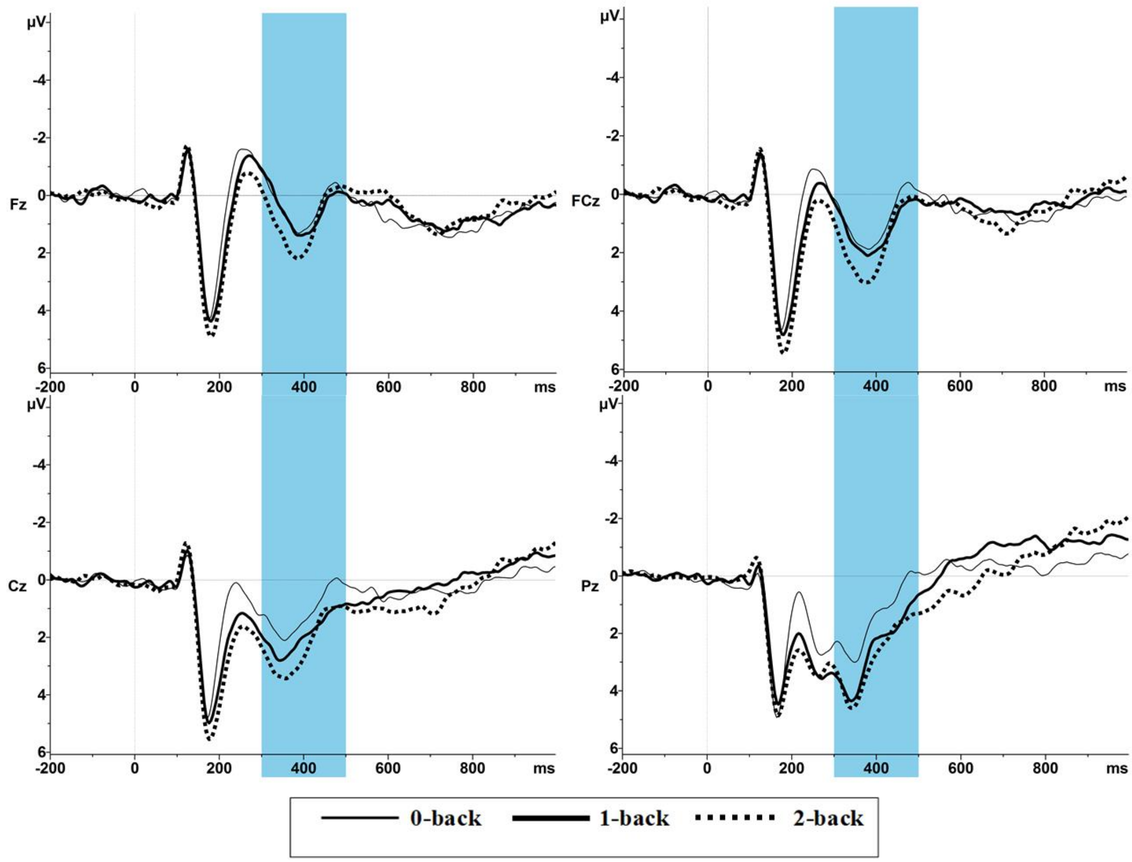

Figure 1. Grand Averaged ERP waveforms combining both groups to show the effect of condition. Negative is plotted upwards.

The P300 analysis showed a significant effect of Group, F (1, 42) =5.43, p=0.025, n_p^2 =0.11. Bilinguals had a mean amplitude of 2.22 μV whereas the mean amplitude for monolinguals was 0.73 μV (Figure 2). P300 amplitude also revealed a main effect of condition, F (2, 84) = 8.85, p<0.001, n_p^2 =0.17 (Figure 1). Bonferroni corrected post-hoc analyses revealed that the 0-back task elicited smaller amplitudes (0.986μV) than both the 1-back (1.511 μV), p=0.02 and 2-back (1.930 μV), p <0.001. There was a significant Site X Group interaction, F (3, 126) =5.78, p=0.004, n_p^2 =0.12. Pairwise comparisons identified differences between monolinguals and bilinguals at Fz (-0.13 μV for monolinguals vs. 1.31 μV for bilinguals, p=0.024); FCz (0.34 μV vs. 2.2 μV, p=0.016), and Cz (0.86 μV vs. 2.70

μV, *p*=0.17). That is, monolinguals exhibited smaller P300 amplitudes compared to bilinguals at Fz, FCz, and Cz across all conditions.

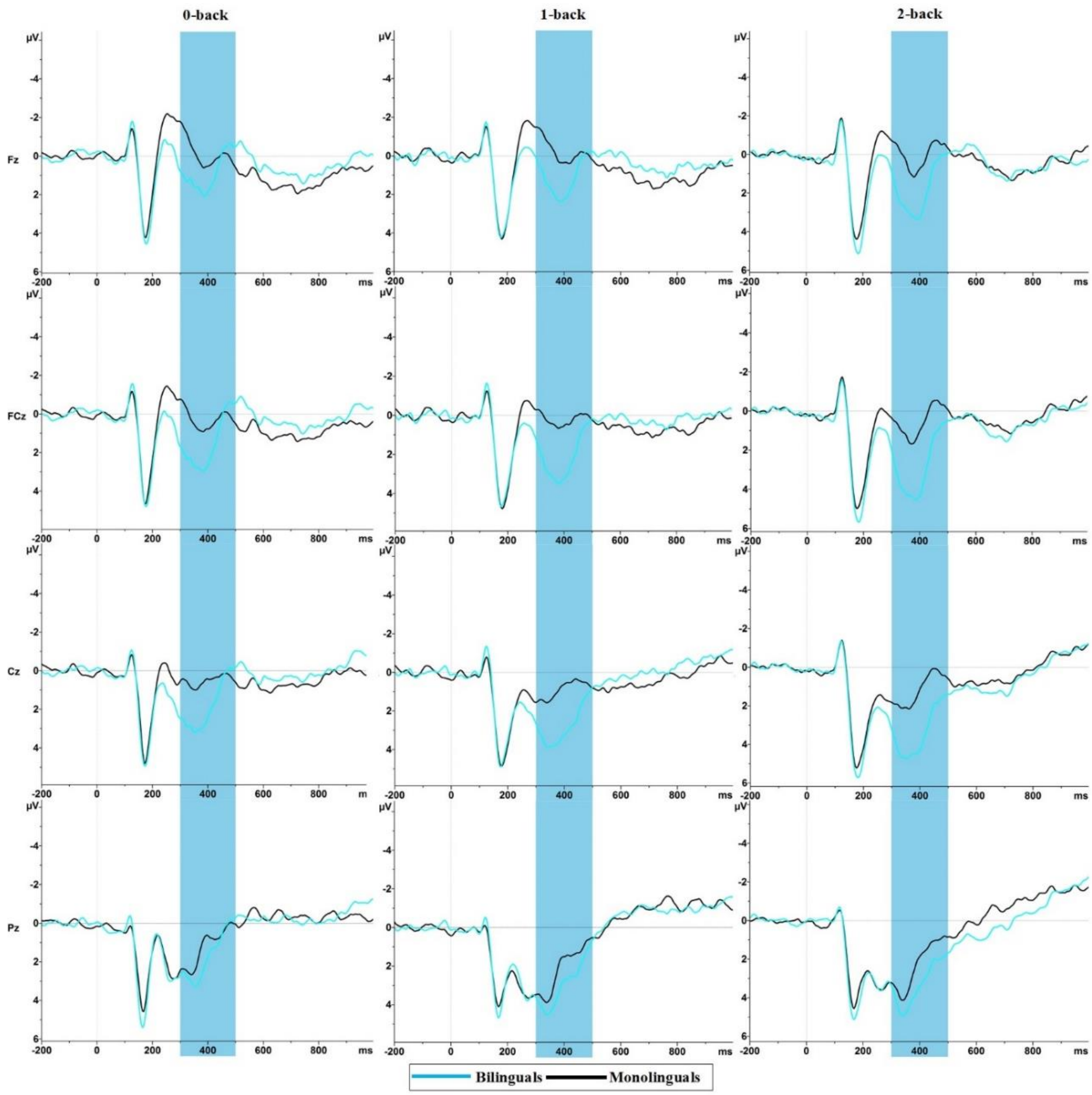

Figure 2. Grand averaged ERP waveforms for bilingual and monolingual young adults during each of the n-back conditions. Negative is plotted upwards.

Discussion

While numerous studies have employed neuroimaging techniques such as ERPs, magnetoencephalography (MEG), and functional magnetic resonance imaging (fMRI), to examine EF differences between bilinguals and monolinguals (Abutalebi et al., 2012; Bialystok, Craik, et al., 2005; Gigi, Anderson, Craik, Grady, & Bialystok, 2010a; Green & Abutalebi, 2016; Kousaie & Phillips, 2012b), to our knowledge the present study is the first to examine the effect of bilingualism on WM performance using ERPs.

In line with previous research (Bialystok, 2009; Blom et al., 2014; Bonifacci & Giombini, 2011; Engel de Abreu & Abreu, 2011; Ratiu & Azuma, 2015), no differences were observed between monolingual and bilingual participants in standardized neuropsychological tasks tapping WM (digit span forward, digit span backward, and letter/number sequencing). Behaviorally, monolinguals and bilinguals responded with similar accuracy and RT in all conditions of the experimental task (0-, 1-, and 2- back). As predicted, longer RTs and lower accuracy were observed in both groups as task difficulty increased.

The P200 and N200 are believed to be involved with early processing for allocation of attention and inhibitory processing (Bennys et al., 2007; Lijffijt et al., 2009) as well as the ability to discriminate between a current stimulus and the representation of one held in memory (Folstein & Van Petten, 2008). Similar P200 latency and amplitude between groups demonstrates that the allocation of attention during a WM task does not differ between monolinguals and bilinguals. Although it was expected that monolinguals would have diminished N200s the similarity between groups suggests that both groups have similar ability to focus attention and discriminate between the target stimulus and the one held in memory.

While previous research has indicated that P300 amplitude declines as WM load increases, due to the availability of fewer cognitive resources (Gevins et al., 1996; Kok, 2001), here we found that P300 amplitude increased with increasing WM load. This finding may reflect participants’ near-ceiling accuracy. High accuracy suggests that participants had sufficient cognitive resources available to complete the task with little difficulty. Bilinguals also exhibited larger P300 amplitudes relative to monolinguals, reflecting differences in cognitive processing. Based on previous research on high and low performers (Daffner et al., 2011), we posit that larger P300 amplitudes in bilinguals demonstrate that they have more cognitive resources available for allocation towards task completion (Kok, 2001) compared to monolinguals, suggesting that bilinguals can complete more difficult tasks with less effort and higher efficiency.

In the absence of behavioral differences, electrophysiological differences between monolinguals and bilinguals during WM processing were found. Future research should replicate this study with a 3-back task to determine if more challenging tasks can elicit both behavioral and neural group differences. To determine whether electrophysiological differences between groups translates into a behavioral cognitive advantage, it would also be beneficial to test bilingual and monolingual older adults. Language group differences are more difficult to detect in young adults because they are at the peak of their cognitive functioning, whereas effects of bilingualism on WM may be easier to detect in older adults due to age-related cognitive declines.

4. Conclusion

While monolinguals and bilinguals performed with similar accuracy and response time in both low and high load WM conditions, group differences were observed in electrophysiological response. Specifically, bilinguals showed significantly larger P300 amplitudes relative to monolinguals, indicating that bilinguals have more resources available to allocate to task completion as WM load increases. These findings indicate that ERPs may be sensitive to cognitive differences that are not revealed by behavioral measures.

References:

Abutalebi, J., Della Rosa, P. A., Green, D. W., Hernandez, M., Scifo, P., Keim, R., ... & Costa, A. (2011). Bilingualism tunes the anterior cingulate cortex for conflict monitoring. *Cerebral cortex, 22*(9), 2076-2086.

Baddeley, A. (2003). Working memory: looking back and looking forward. *Nature Reviews. Neuroscience, 4*(10), 829.

Badzakova-Trajkov, G. (2008). *A behavioural and functional imaging investigation of Stroop task performance in late proficient bilinguals* (Doctoral dissertation, ResearchSpace@ Auckland).

Bain, B. (1975). Toward an integration of Piaget and Vygotsky: Bilingual considerations. *Linguistics,* 13(160), 5-20.

Barac, R., Moreno, S., & Bialystok, E. (2016). Behavioral and electrophysiological differences in executive control between monolingual and bilingual children. *Child development*, *87*(4), 1277-1290.

Bennys, K., Portet, F., Touchon, J., & Rondouin, G. (2007). Diagnostic value of event-related evoked potentials N200 and P300 subcomponents in early diagnosis of Alzheimer's disease and mild cognitive impairment. *Journal of Clinical Neurophysiology*, *24*(5), 405-412.

Bialystok, E. (2009). Bilingualism: The good, the bad, and the indifferent. *Bilingualism: Language and cognition, 12*(1), 3-11.

Bialystok, E., Craik, F. I., Grady, C., Chau, W., Ishii, R., Gunji, A., & Pantev, C. (2005). Effect of bilingualism on cognitive control in the Simon task: evidence from MEG. *NeuroImage*, *24*(1), 40-49.

Bialystok, E., Craik, F. I., Klein, R., & Viswanathan, M. (2004). Bilingualism, aging, and cognitive control: evidence from the Simon task. *Psychology and aging*, *19*(2), 290.

Bialystok, E., & Martin, M. M. (2004). Attention and inhibition in bilingual children: Evidence from the dimensional change card sort task. *Developmental science*, *7*(3), 325-339.

Blom, E., Küntay, A. C., Messer, M., Verhagen, J., & Leseman, P. (2014). The benefits of being bilingual: Working memory in bilingual Turkish–Dutch children. *Journal of experimental child psychology*, *128*, 105-119.

Bonifacci, P., Giombini, L., Bellocchi, S., & Contento, S. (2011). Speed of processing, anticipation, inhibition and working memory in bilinguals. *Developmental science*, *14*(2), 256-269.

Daffner, K. R., Chong, H., Sun, X., Tarbi, E. C., Riis, J. L., McGinnis, S. M., & Holcomb, P. J. (2011). Mechanisms underlying age-and performance-related differences in working memory. *Journal of cognitive neuroscience, 23*(6), 1298-1314.

Diamond, A. (2013). Executive functions. *Annual review of psychology*, *64*, 135-168.

Duñabeitia, J. A., Hernández, J. A., Antón, E., Macizo, P., Estévez, A., Fuentes, L. J., & Carreiras, M. (2014). The inhibitory advantage in bilingual children revisited. *Experimental psychology*.

Engel de Abreu, P. M. (2011). Working memory in multilingual children: Is there a bilingual effect? *Memory*, *19*(5), 529-537.

Finnigan, S., O'Connell, R. G., Cummins, T. D., Broughton, M., & Robertson, I. H. (2011). ERP measures indicate both attention and working memory encoding decrements in aging. *Psychophysiology*, *48*(5), 601-611.

Folstein, J. R., & Van Petten, C. (2008). Influence of cognitive control and mismatch on the N2 component of the ERP: a review. *Psychophysiology*, *45*(1), 152-170.

Gathercole, V. C. M., Thomas, E. M., Kennedy, I., Prys, C., Young, N., Guasch, N. V., ... & Jones, L. (2014). Does language dominance affect cognitive performance in bilinguals? Lifespan evidence from preschoolers through older adults on card sorting, Simon, and metalinguistic tasks. *Frontiers in Psychology*, *5*.

Gevins, A., Smith, M. E., Le, J., Leong, H., Bennett, J., Martin, N., ... & Whitfield, S. (1996). High resolution evoked potential imaging of the cortical dynamics of human working memory. *Electroencephalography and clinical neurophysiology*, *98*(4), 327-348.

Goldman, M. C., Negen, J., & Sarnecka, B. W. (2014). Are bilingual children better at ignoring perceptually misleading information? A novel test. *Developmental science*, *17*(6), 956-964.

Grant, D. A., & Berg, E. (1948). A behavioral analysis of degree of reinforcement and ease of shifting to new responses in a Weigl-type card-sorting problem. *Journal of experimental psychology*, *38*(4), 404.

Green, D. W., & Abutalebi, J. (2016). Language control and the neuroanatomy of bilingualism: in praise of variety. *Language, Cognition and Neuroscience*, *31*(3), 340-344.

Greenhouse, S. W., & Geisser, S. (1959). On methods in the analysis of profile data. *Psychometrika*, *24*(2), 95-112.

Grundy, J. G., Anderson, J. A., & Bialystok, E. (2017). Bilinguals have more complex EEG brain signals in occipital regions than monolinguals. *NeuroImage*, *159*, 280-288.

Kaplan, E., Goodglass, H., Weintraub, S., & Segal, O. (1983). Boston Naming Test Lea & Febi.

Kessler, C., & Quinn, M. E. (1987). Language minority children's linguistic and cognitive creativity. *Journal of Multilingual & Multicultural Development*, *8*(1-2), 173-186.

Kok, A. (2001). On the utility of P3 amplitude as a measure of processing capacity. *Psychophysiology*, *38*(3), 557-577.

Kousaie, S., & Phillips, N. A. (2012). Conflict monitoring and resolution: Are two languages better than one? Evidence from reaction time and event-related brain potentials. *Brain research*, *1446*, 71-90.

Kudo, M., & Swanson, H. L. (2014). Are there advantages for additive bilinguals in working memory tasks? *Learning and Individual Differences*, *35*, 96-102.

Lijffijt, M., Lane, S. D., Meier, S. L., Boutros, N. N., Burroughs, S., Steinberg, J. L., ... & Swann, A. C. (2009). P50, N100, and P200 sensory gating: relationships with behavioral inhibition, attention, and working memory. *Psychophysiology*, *46*(5), 1059-1068.

Luck, S. J. (2014). *An introduction to the event-related potential technique*. MIT press.

Luk, G., Anderson, J. A., Craik, F. I., Grady, C., & Bialystok, E. (2010). Distinct neural correlates for two types of inhibition in bilinguals: Response inhibition versus interference suppression. *Brain and cognition*, *74*(3), 347-357.

Mertens, R., & Polich, J. (1997). P300 from a single-stimulus paradigm: passive versus active tasks and stimulus modality. *Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section*, *104*(6), 488-497.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: A latent variable analysis. *Cognitive psychology*, *41*(1), 49-100.

Morales, J., Calvo, A., & Bialystok, E. (2013). Working memory development in monolingual and bilingual children. *Journal of experimental child psychology*, *114*(2), 187-202.

Patel, S. H., & Azzam, P. N. (2005). Characterization of N200 and P300: selected studies of the event-related potential. *International journal of medical sciences*, *2*(4), 147.

Peal, E., & Lambert, W. E. (1962). The relation of bilingualism to intelligence. *Psychological Monographs: general and applied*, *76*(27), 1.

Perrin, F., Pernier, J., Bertrand, O., & Echallier, J. F. (1989). Spherical splines for scalp potential and current density mapping. *Electroencephalography and clinical neurophysiology*, *72*(2), 184-187.

Polich, J. (1996). Meta-analysis of P300 normative aging studies. *Psychophysiology*, *33*(4), 334-353.

Polich, J. (2007). Updating P300: an integrative theory of P3a and P3b. *Clinical neurophysiology*, *118*(10), 2128-2148.

Prior, A., & Gollan, T. H. (2011). Good language-switchers are good task-switchers: Evidence from Spanish–English and Mandarin–English bilinguals. *Journal of the International Neuropsychological Society*, *17*(4), 682-691.

Ratiu, I., & Azuma, T. (2015). Working memory capacity: Is there a bilingual advantage? *Journal of Cognitive Psychology*, *27*(1), 1-11.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of experimental psychology*, *18*(6), 643.

Wechsler, D. (1997). *Wechsler memory scale (WMS-III)* (Vol. 14). San Antonio, TX: Psychological corporation.

End Notes

[i] Consistent with previous studies, we refer to the parietally-maximal P3b as the P300.

[ii] The n-back was employed as a delay task after an emotional faces paradigm where participants were required to state if a picture was emotionally arousing.

Part 1: Paradigm 2 (Study 2)

Study 2 was also published in Bilingualism: Language and Cognition and is formatted in accordance with the requirements of that journal.

Morrison, C., Kamal, F., & Taler, V. (2019). Monolinguals and bilinguals respond differently to a delayed matching-to-sample task: an ERP study. *Bilingualism: Language and Cognition* (2019): 1-11 DOI: 10.1017/S1366728919000816

In Study 1, young adult English monolinguals and English-French bilinguals completed the n-back working memory task while EEG, accuracy, and reaction time were recorded. It was observed that monolinguals and bilinguals did not differ with respect to accuracy or reaction time. However, monolinguals exhibited smaller P3b amplitudes relative to bilinguals. Using a similar sample of young adults to the n-back, we employed this second paradigm to examine if young adult English monolinguals and English-French bilinguals display different ERPs during a delayed matching-to-sample task. The sample consisted of 37 (out of 54) participants who also completed the n-back task. The delayed matching-to-sample task was employed because it is a span task that may activate the phonological loop. The phonological loop is a component of working memory that has been associated with language acquisition and second language learning. If monolinguals and bilinguals differ in working memory it might be more observable in a task that activates processes associated with language functioning.

Study 2: Monolinguals and bilinguals respond differently to a delayed matching-to-sample task: an ERP study

Short title: Bilinguals differ from monolinguals during a DMS task
Full title: 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 proficient 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		t-test and *p*-values
	Monolingual	Bilingual	
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 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.

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.

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 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.

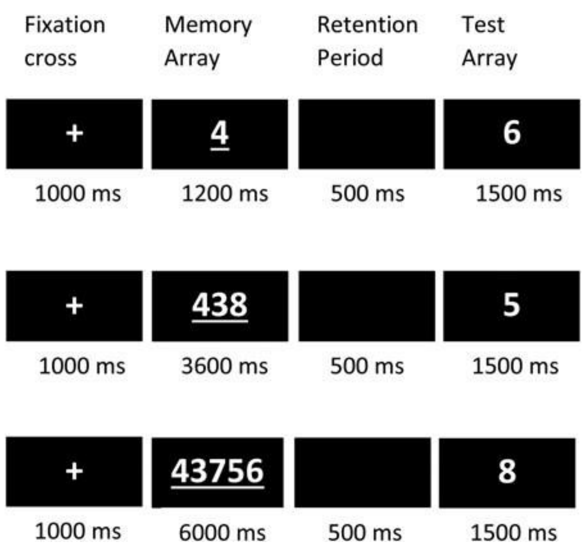

Figure 1. Description of the task: an example of the stimuli used for each condition and timing of stimulus presentation. In all examples shown above participants would respond “no” by pressing the “L” key to state that the probe does not match the memory array.

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, $n^2_p = 0.28$). 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, $n^2_p = 0.81$). 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, frontocentral, 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 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, $F(2,104) = 3.75$, $p = .009$, $n^2_p = 0.10$). Similarly, low load elicited a shorter P2 latency (193.69 ms) than high load (202.25 ms, p = .013), (main effect of Condition $F(2,104) = 3.75$, $p = .027$, $n^2_p = 0.07$).

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, $F(2,104) =20.63$, $p< .001$, $n^2_p =0.28$). 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, $F(1,52) = 3.83$, $p = .056$, $n^2_p = 0.08$).

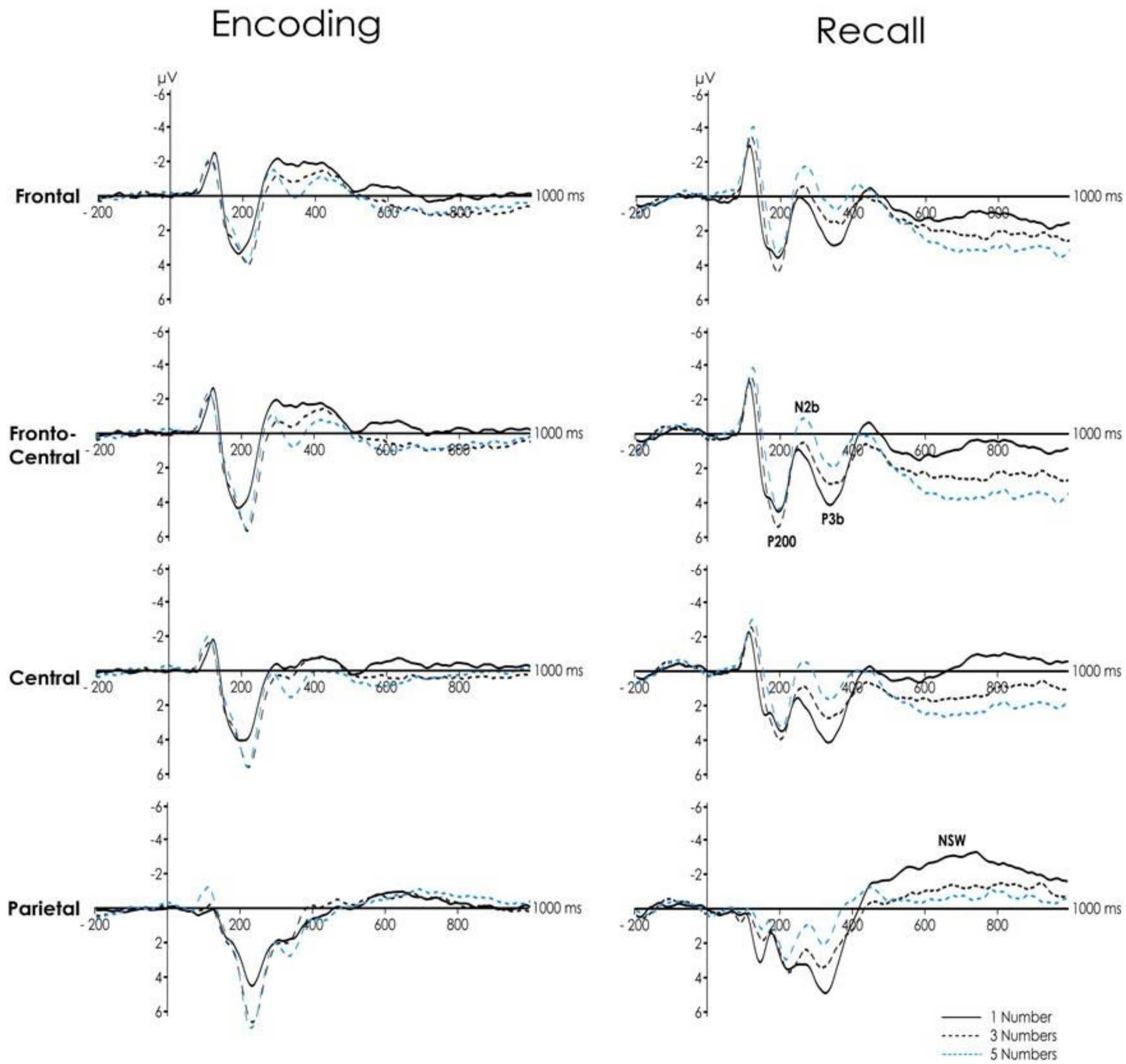

Figure 2: Grand averaged ERP waveforms collapsing across groups to show the effects of condition during encoding and retrieval. Averages at frontal (F3, Fz, F4), fronto-central (FC1, FCz, FC2), central (C3, Cz, C4), and parietal (P3, Pz, P4) regions are shown. Negative is plotted up.

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 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, $F(2,104) = 11.92$, $p < .001$, $n^2_p = .19$). 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, $F(1,52) = 5.39$, $p = .024$, $n^2_p = 0.09$). Amplitude increased with increasing task difficulty (main effect of task difficulty, $F(2, 104) = 14.15$, $p < .001$, $n^2_p = 0.21$). 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, $F(2, 104) = 4.38$, $p = 0.019$, $n^2_p = 0.08$). 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, $F(1,52) = 5.41$, $p = .024$, $n^2_p = 0.10$). 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, $F(2,104) = 14.06$, $p < .001$, $n^2_p = 0.22$).

As shown by a main effect of Group $F(1,52) = 8.41$, $p = .005$, $n^2_p = 0.14$, 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, $F(2,104) = 12.49$, $p < .001$, $n^2_p = 0.39$).

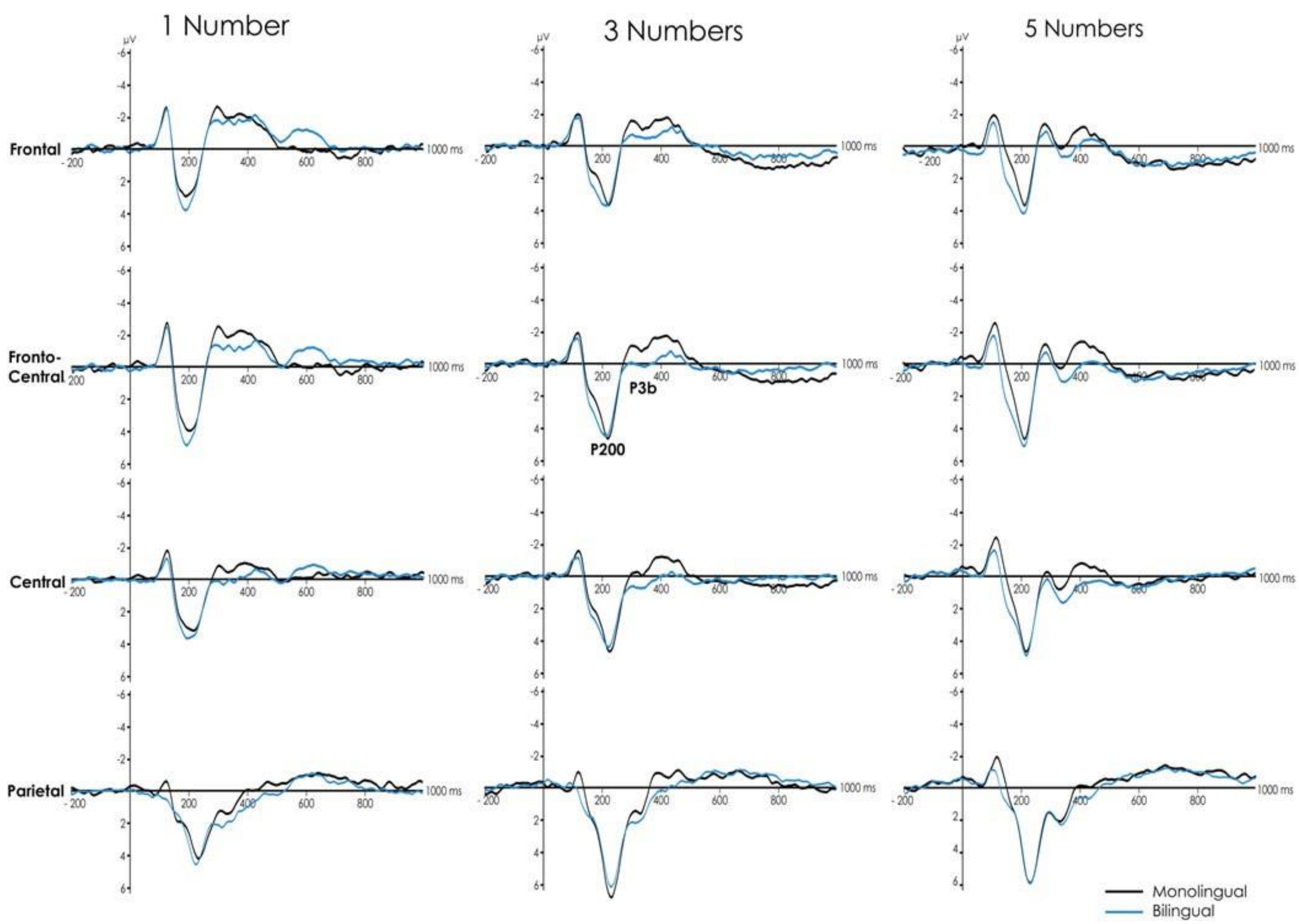

Figure 3: Grand averaged ERP waveforms for monolingual and bilingual young adults during encoding for each of the conditions. Bilinguals exhibited larger P3b amplitudes than monolinguals, while P200s were similar in the two groups.

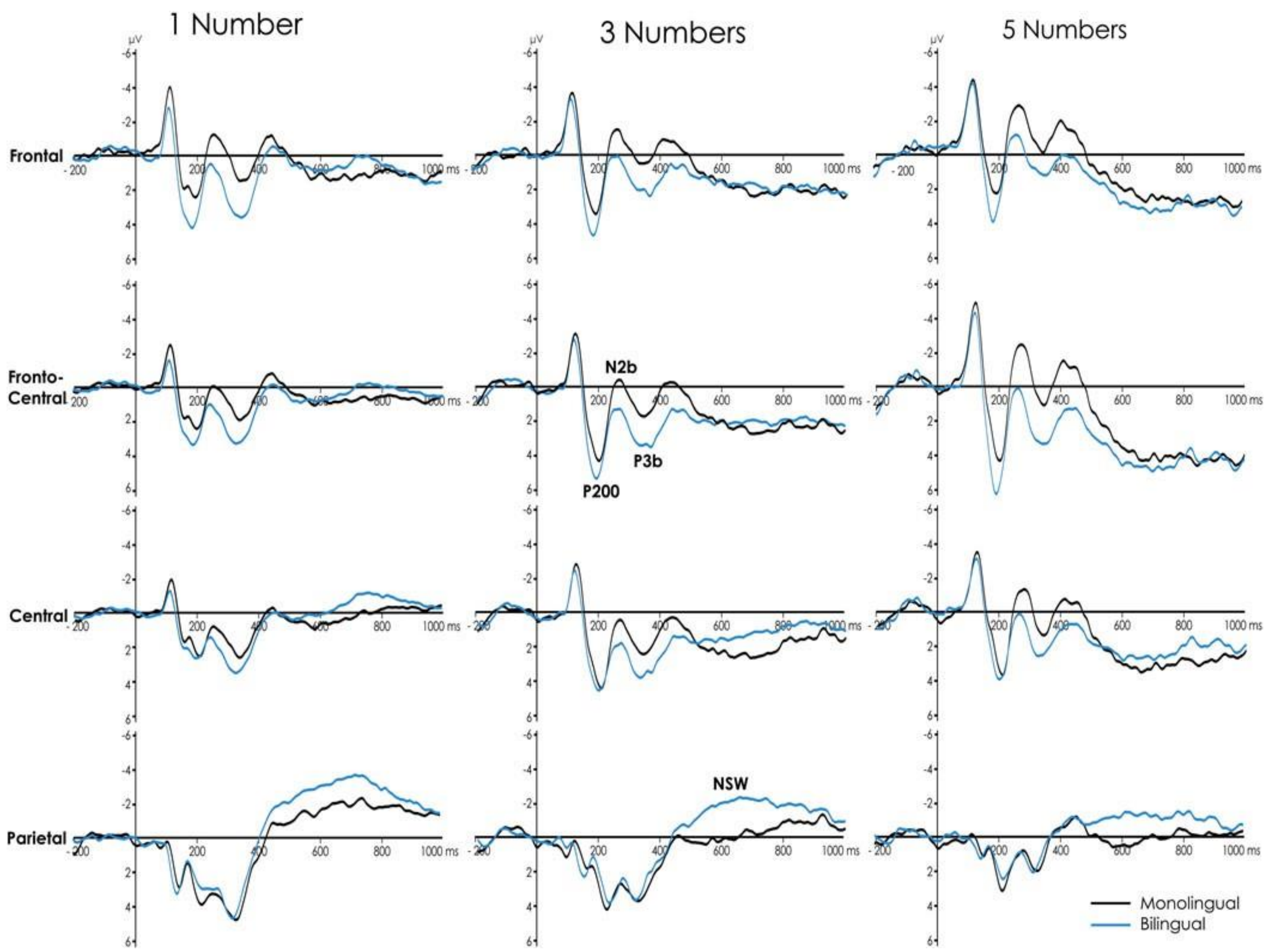

Figure 4: Grand averaged ERP waveforms for monolingual and bilingual young adults during retrieval for each of the conditions. Bilinguals exhibited smaller N2b and NSW amplitudes and larger P3b amplitudes than monolinguals.

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 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 highload (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 proficient 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.

References

Atkins, P. W. B., & Baddeley, A. D. (1998). Working memory and distributed vocabulary learning. *Applied Psycholinguistics, 19*(4), 537–552. https://doi.org/doi:10.1017/S0142716400010353

Axmacher, N., Lenz, S., Haupt, S., Elger, C. E., & Fell, J. (2010). Electrophysiological signature of working and long-term memory interaction in the human hippocampus. *European Journal of Neuroscience*, 31(1), 177-188. https://doi.org/10.1111/j.1460-9568.2009.07041.x

Axmacher, N., Mormann, F., Fernández, G., Cohen, M. X., Elger, C. E., & Fell, J. (2007). Sustained neural activity patterns during working memory in the human medial temporal lobe. *Journal of Neuroscience*, 27(29), 7807-7816. https://doi.org/10.1523/JNEUROSCI.0962-07.2007

Baddeley, A. (2000). The episodic buffer : a new component of working memory? *Trends in Cognitive Sciences, 4*(11), 417–423. https://doi.org/10.1016/S1364-6613(00)01538-2

Baddeley, A. (2003). Working memory: looking back and looking forward. *Nature Reviews Neuroscience*, *4*(10), 829–839. DOI: doi:10.1038/nrn1201

Baddeley, A., Gathercole, S., & Papagno, C. (1998). The phonological loop as a language learning device. *Psychological Review*, *105*(1), 158. DOI: 10.1037/0033-295X.105.1.158

Bennys, K., Portet, F., Touchon, J., & Rondouin, G. (2007). Diagnostic value of event-related evoked potentials N200 and P300 subcomponents in early diagnosis of Alzheimer's disease and mild cognitive impairment. *Journal of Clinical Neurophysiology*, *24*(5), 405-412. DOI: 10.1097/WNP.0b013e31815068d5

Blom, E., Küntay, A. C., Messer, M., Verhagen, J., & Leseman, P. (2014). The benefits of being bilingual: Working memory in bilingual Turkish–Dutch children. *Journal of Experimental Child Psychology*, *128*, 105-119. https://doi.org/10.1016/j.jecp.2014.06.007

Borkowski, J. G., Benton, A. L., & Spreen, O. (1967). Word fluency and brain damage. *Neuropsychologia*, 5(2), 135-140. https://doi.org/10.1016/0028-3932(67)90015-2

Broster, L. S., Jenkins, S. L., Holmes, S. D., Edwards, M. G., Jicha, G. A., & Jiang, Y. (2018). Electrophysiological repetition effects in persons with mild cognitive impairment depend upon working memory demand. *Neuropsychologia*, 117, 13-25. https://doi.org/10.1016/j.neuropsychologia.2018.05.001

Cain, K., Oakhill, J., & Bryant, P. (2004). Children's reading comprehension ability: Concurrent prediction by working memory, verbal ability, and component skills. *Journal of Educational Psychology*, *96*(1), 31. https://doi.org/10.1037/0022-0663.96.1.31

Caplan, D., & Waters, G. S. (1999). Verbal working memory and sentence comprehension. *Behavioral and Brain Sciences*, *22*(1), 77-94. https://doi.org/10.1017/S0140525X99001788

Daffner, K. R., Chong, H., Sun, X., Tarbi, E. C., Riis, J. L., McGinnis, S. M., & Holcomb, P. J. (2011). Mechanisms underlying age-and performance-related differences in working memory. *Journal of Cognitive Neuroscience*, *23*(6), 1298-1314. https://doi.org/10.1162/jocn.2010.21540.Mechanisms

Diamond, A. (2013). Executive functions. *Annual Review of Psychology*, *64*, 135-168. https://doi.org/10.1146/annurev-psych-113011-143750

Donchin, E. (1981). Surprise!… surprise? *Psychophysiology*, *18*(5), 493-523. https://doi.org/10.1111/j.1469-8986.1981.tb01815.x

Engel de Abreu, P. M. (2011). Working memory in multilingual children: Is there a bilingual effect? *Memory*, *19*(5), 529-537. https://doi.org/10.1080/09658211.2011.590504

Finnigan, S., O'Connell, R. G., Cummins, T. D., Broughton, M., & Robertson, I. H. (2011). ERP measures indicate both attention and working memory encoding decrements in aging. *Psychophysiology*, *48*(5), 601-611. https://doi.org/10.1111/j.1469-8986.2010.01128.x

Folstein, J. R., & Van Petten, C. (2008). Influence of cognitive control and mismatch on the N2 component of the ERP: a review. *Psychophysiology*, *45*(1), 152-170. https://doi.org/10.1111/j.1469-8986.2007.00602.x

Gathercole, S. E., & Pickering, S. J. (2000). Working memory deficits in children with low achievements in the national curriculum at 7 years of age. *British Journal of Educational Psychology*, *70*(2), 177-194.

Germano, C., & Kinsella, G. J. (2005). Working memory and learning in early Alzheimer's disease. *Neuropsychology Review*, *15*(1), 1-10. https://doi.org/10.1007/s11065-005-3583-7

Goldstein, E. B. (2014). Cognitive Psychology: Connecting mind, research and everyday experience (pp. 134–136). Nelson Education.

Grant, D. A., & Berg, E. (1948). A behavioral analysis of degree of reinforcement and ease of shifting to new responses in a Weigl-type card-sorting problem. *Journal of Experimental Psychology*, *38*(4), 404. DOI:10.1037/h0059831

Grundy, J. G., Anderson, J. A., & Bialystok, E. (2017). Bilinguals have more complex EEG brain signals in occipital regions than monolinguals. *NeuroImage*, *159,* 280-288. https://doi.org/10.1016/j.neuroimage.2017.07.06

Grundy, J. G., & Timmer, K. (2017). Bilingualism and working memory capacity: A comprehensive meta-analysis. *Second Language Research*, 33(3), 325-340. https://doi.org/10.1177/0267658316678286.

Just, M. A., & Carpenter, P. A. (1992). A capacity theory of comprehension: individual differences in working memory. *Psychological Review*, *99*(1), 122.

Kaplan, E., Goodglass, H., Weintraub, S., & Segal, O. (1983). *Boston Naming Test*. Philadelphia: Lea & Febiger.

Kleen, J. K., Testorf, M. E., Roberts, D. W., Scott, R. C., Jobst, B. J., Holmes, G. L., & Lenck-Santini, P. P. (2016). Oscillation phase locking and late erp components of intracranial hippocampal recordings correlate to patient performance in a working memory task. *Frontiers in Human Neuroscience,* 10, 287. https://doi.org/10.3389/fnhum.2016.00287

Kok, A. (2001). On the utility of P3 amplitude as a measure of processing capacity. *Psychophysiology*, *38,* 557–577. https://doi.org/10.1016/S0167-8760(98)90168-4

Kousaie, S., & Phillips, N. A. (2012). Conflict monitoring and resolution: Are two languages better than one? Evidence from reaction time and event-related brain potentials. *Brain Research*, *1446*, 71-90. https://doi.org/10.1016/j.lindif.2014.07.019

Kudo, M., & Swanson, H. L. (2014). Are there advantages for additive bilinguals in working memory tasks? *Learning and Individual Differences*, *35*, 96-102. https://doi.org/10.1016/j.lindif.2014.07.019

Li, B. Y., Tang, H. D., & Chen, S. D. (2016). Retrieval deficiency in brain activity of working memory in amnesic mild cognitive impairment patients: a brain event-related potentials study. *Frontiers in Aging Neurowscience, 8*. https://doi.org/10.3389/fnagi.2016.00054

Lijffijt, M., Lane, S. D., Meier, S. L., Boutros, N. N., Burroughs, S., Steinberg, J. L., ... & Swann, A. C. (2009). P50, N100, and P200 sensory gating: relationships with behavioral inhibition, attention, and working memory. *Psychophysiology*, *46*(5), 1059-1068. https://doi.org/10.1111/j.1469-8986.2009.00845.x.P50

Luck, S. (2014). An Introduction to the Event-related Potential Technique. Cambridge, MA: The MIT Press.

Makeig, S., Bell, A. J., Jung, T. P., & Sejnowski, T. J. (1996). Independent component analysis of electroencephalographic data. *In Advances in Neural Information Processing Systems*, 145-152.

Mecklinger, A., & Pfeifer, E. (1996). Event-related potentials reveal topographical and temporal distinct neuronal activation patterns for spatial and object working memory. *Cognitive Brain Research*, 4(3), 211-224.

Mertens, R., & Polich, J. (1997). P300 from a single-stimulus paradigm: passive versus active tasks and stimulus modality. *Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section*, *104*(6), 488-497. https://doi.org/10.1016/S0926-6410(96)00034-1

Mormann, F., Fell, J., Axmacher, N., Weber, B., Lehnertz, K., Elger, C. E., & Fernández, G. (2005). Phase/amplitude reset and theta–gamma interaction in the human medial temporal lobe during a continuous word recognition memory task. *Hippocampus*, *15*(7), 890-900.

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

Morrison, C., Kamal, F., & Taler, V. (2018). The influence of bilingualism on working memory event-related potentials. *Bilingualism: Language and Cognition,* 22(1), 191-199. https://doi.org/10.1017/S1366728918000391

Ontario Ministry of Education. (2013). The Ontario Curriculum. French as a second language (ISBN 978-1-4606-2446-3). Queens Printer for Ontario.

Ontario Ministry of Education. (2014). The Ontario Curriculum, Grades 9 to 12. French as a second language (ISBN 978-1-4606-2449-4). Queens Printer for Ontario.

Patel, S. H., & Azzam, P. N. (2005). Characterization of N200 and P300 : Selected Studies of the Event-Related Potential. *International Journal of Medical Sciences, 2*(4), 147–154.

Perrin, F., Pernier, J., Bertrand, O., Echallier, J. F., Inserm, U., Thomas, C. A., & France, L. (1989). Spherical splines for scalp potential and current density mapping. *Electroencephalography and Clinical Neurophysiology*, 72(2),184–187. DOI: 10.1016/0013-4694(89)90180-6

Pfefferbaum, A., Wenegrat, B. G., Ford, J. M., Roth, W. T., & Kopell, B. S. (1984). Clinical application of the P3 component of event-related potentials. II. Dementia, depression and schizophrenia. *Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section*, *59*(2), 104-124. https://doi.org/10.1016/0168-5597(84)90027-3

Pinal, D., Zurrón, M., & Díaz, F. (2014). Effects of load and maintenance duration on the time course of information encoding and retrieval in working memory: from perceptual analysis to post-categorization processes. *Frontiers in Human Neuroscience, 8*. https://doi.org/10.3389/fnhum.2014.00165

Pinal, D., Zurrón, M., & Díaz, F. (2015). Age-related changes in brain activity are specific for high order cognitive processes during successful encoding of information in working memory. *Frontiers in Aging Neuroscience,* 7, 75. https://doi.org/10.3389/fnagi.2015.00075

Polich, J. (1996). Meta-analysis of P300 normative aging studies. *Psychophysiology, 33*, 334–353. DOI: 10.1111/j.1469-8986.1996.tb01058.x

Polich, J. (2007). Updating P300: An integrative theory of P3a and P3b. *Clinical Neurophysiology*, *118*(10), 2128–2148. https://doi.org/10.1016/j.clinph.2007.04.019

Ratiu, I., & Azuma, T. (2015). Working memory capacity: Is there a bilingual advantage? *Journal of Cognitive Psychology*, *27*(1), 1-11. https://doi.org/10.1080/20445911.2014.976226

Ruchkin, D. S., & Sutton, S. (1983). Positive Slow Wave and P300: Association and Disassociation. In Advances in Psychology (Vol. 10, pp. 233-250). North-Holland.

Service, E. (1992). Phonology, working memory, and foreign-language learning. *The Quarterly Journal of Experimental Psychology*, *45*(1), 21-50. https://doi.org/10.1080/14640749208401314

Statistics Canada. (2017, August 2). Census in Brief: English-French bilingualism reaches new heights. Retrieved from https://www12.statcan.gc.ca/census-recensement/2016/as-sa/98-200-x/2016009/98-200-x2016009-eng.cfm

Statistics Canada. (2019, August 9). Census Profile, 2016 Census Ottawa, City [Census subdivision], Ontario and Ottawa, Census division [Census division], Ontario. Retrieved from https://www12.statcan.gc.ca/census-recensement/2016/dp-pd/prof/details/page.cfm?Lang=E&Geo1=CSD&Code1=3506008&Geo2=CD&Code2=3506&Data=Count&SearchText=Ottawa&SearchType=Begins&SearchPR=01&B1=Language&TABID=1

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, 18(6), 643.

Studer, P., Wangler, S., Diruf, M. S., Kratz, O., Moll, G. H., & Heinrich, H. (2010). ERP effects of methylphenidate and working memory load in healthy adults during a serial visual working memory task. *Neuroscience Letters*, 482(2), 172-176. https://doi.org/10.1016/j.neulet.2010.07.030

Veen, V. Van, & Carter, C. S. (2002). The anterior cingulate as a conflict monitor: fMRI and ERP studies. *Physiology & Behavior*, *77*(4-5), 477-482. DOI: 10.1016/S0031-9384(02)00930-7

Wechsler, D. (1997). *Wechsler Memory Scale (WMS-III)* (Vol. 14). San Antonion: TX: Psychological Corporation.

Part 2: (Paradigm 1) Study 3

Study 3 is in the final editing stages to be submitted to international Journal of Psychophysiology. The manuscript is thus formatted in accordance with the requirements of that journal.

Morrison, C., & Taler, V. Bilinguals exhibit ERP differences in the absence of a "bilingual advantage"

Study 3 was designed as a follow-up to Study 1, which compared young adult English monolinguals to English-French bilinguals during an n-back working memory task. In that study, it was observed that monolinguals and bilinguals did not differ with respect to accuracy or reaction time. However, monolinguals exhibited smaller P3b amplitudes relative to bilinguals. It was hypothesized that young adults did not display any behavioral differences because they are at the peak of their cognitive functioning. Study 3 was thus designed to determine if older adults, that experience age-related cognitive changes benefit from cognitive advantages offered by bilingualism. The sample of young adults from Study 1 was compared to the older adult monolinguals and bilinguals. In addition to the past sample of young adults, an additional 19 young adults were recruited to match the sample size of the older adult participants.

Study 3: Bilinguals exhibit ERP differences in the absence of a “bilingual advantage”

Title: Bilinguals exhibit ERP differences in the absence of a “bilingual advantage”
Short title: Effects of age and bilingualism on ERPs

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Keywords: Event-related potentials, bilingualism, working memory, n-back older adults

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Abstract

Although some research has demonstrated a bilingual cognitive advantage, several studies have failed to replicate this finding. The current study used behavioral and electrophysiological measures to examine whether working memory capacity and neural activity differed in a sample of younger and older monolingual and bilingual adults. Younger and older adults exhibited different ERP patterns during task completion, suggesting that older adults have less efficient working memory processing and require more resources at lower levels of task difficulty. Although bilinguals exhibited no behavioral or neuropsychological advantages relative to monolinguals, they did show larger P3b amplitudes, suggesting that bilingualism may lead to altered neural activity patterns during a working memory task in the absence of performance advantages. The present study provides evidence for ERP differences due to both bilingualism and age but does not indicate a bilingual advantage in working memory.

1. Introduction

In recent years, we have seen an increasing prevalence of bilingualism around the world and a large body of literature has focused on investigating the cognitive advantages that bilingualism may provide. Most of this research has focused on determining if there is a bilingual advantage in executive function. While a number of studies have demonstrated such an advantage (e.g., Badzakova-Trajkov, 2008; Prior & Gollan, 2011; see Bialystok 2017 for review), not all studies have replicated this finding (e.g. Paap & Greenberg, 2013), and others have replicated the results in some, but not all, conditions (Chung-Fat-Yim, Himel, & Bialystok, 2019). To reduce these inconsistencies, researchers have suggested that research into the potential impact of bilingualism on cognitive processing should include populations that may be experiencing cognitive changes (e.g., older adults), and should use more sensitive tools (e.g., event-related potentials; ERPs) (Dick et al., 2018; Kousaie & Taler, 2015).

In addition to the relatively well-studied domain of executive function, cognitive differences between monolinguals and bilinguals may also be observed in working memory (WM) (Morrison, Kamal, Le, & Taler, 2019; Morrison, Kamal, & Taler, 2018). WM is the limited capacity memory system responsible for maintaining and manipulating information over short periods (Baddeley, 2003), and has been linked to language comprehension and word learning (Atkins & Baddeley, 1998), suggesting a possible association between WM and bilingualism. To date, research investigating the effects of bilingualism on WM has found inconsistent results: some studies have shown enhanced WM performance in bilinguals compared to monolinguals (Bialystok & Feng, 2009; Kudo & Swanson, 2014; Morales, Calvo, & Bialystok, 2013) while others have reported no advantage (Blom, Küntay, Messer, Verhagen, & Leseman, 2014; Engel de Abreu & Abreu, 2011; Lukasik, Lehtonen, Soveri, Waris, & Jylkka, 2018; Ratiu & Azuma, 2015). A recent meta-analysis reported that bilinguals exhibit a larger WM capacity than monolinguals during span tasks (Grundy & Timmer, 2017).

One possible account for these inconsistent findings is that most research has been conducted on young adults, who are at the peak of their cognitive functioning and in whom any additional cognitive advantages offered by bilingualism may be difficult to measure. Declines in WM have been observed in older adults (Brockmole & Logie, 2013; Park et al., 2002); thus, any bilingualism-related advantage may be easier to detect in this population. Nevertheless, a recent study examining older adult monolinguals and bilinguals observed no bilingual advantage on a battery of 12 different executive function tasks including WM (Nichols, Wild, Stojanoski, Battista, & Owen, 2020).

In addition to declines in cognitive processes, older adults also exhibit changes in brain activity compared to young adults. One hypothesis, the Compensation-Related Utilization of Neural Circuits Hypothesis (CRUNCH; Reuter-Lorenz & Lustig, 2005), holds that, due to reductions in efficiency of cognitive processing in older adults, they show increased activation at lower levels of task difficulty compared to young adults. With increasing task demand, fewer resources are available, leading to reduced brain activation (Schneider-Garces et al., 2010).

In recent years, aging research has focused on ways to prevent or mitigate cognitive decline (e.g., Christensen, 2001). Some studies have suggested that being bilingual may help maintain later-life cognitive functioning (Bialystok, Martin, & Viswanathan, 2005; Kavé, Eyal, Shorek, & Cohen-Mansfield, 2008) and even delay the onset of dementia (Bialystok, Craik, & Freedman, 2007). However, several studies have failed to find cognitive advantages in older adult bilinguals compared to monolinguals (e.g., Antón, Fernández García, Carreiras, & Duñabeitia, 2016; Kousaie & Phillips, 2012; Nichols et al., 2020). One possible reason for a failure to detect differences between monolinguals and bilinguals may be the use of measures that are not sensitive to subtle processing differences. Here, we used both behavioral and electrophysiological measures (ERPs) to examine WM capacity and processing in monolinguals and bilinguals. We had participants complete an n-back task while electroencephalography (EEG), accuracy, and reaction time were recorded.

Neurophysiological correlates of working memory processing are reflected by the P2, N2, and P3b ERP components. The anterior maximal P2 component is a positive-going component that occurs about 150-300 ms after stimulus presentation. It is associated with WM processing, with lower amplitudes representing poorer performance (Finnigan, O'Connell, Cummins, Broughton, & Robertson, 2011). The N2 is an anterior negative-going component that occurs approximately 200-350 ms post-stimulus presentation (Folstein & Van Petten, 2008). This component indexes the effort required to complete a task (Fitzgerald & Picton, 1983; Jodo & Kayama, 1992) as well as the ability to correctly discriminate the current stimulus from that of one held in memory (Folstein & Van Petten, 2008; Patel & Azzam, 2005). Finally, the P3b is a positive-going waveform that occurs approximately 300-600 ms post-stimulus presentation and is thought to be related to the allocation of WM resources, with a decrease in amplitude associated with fewer resources available for task completion (Kok, 2001; Polich, 2007). Although typically parietally maximal (Polich, 2007), the P3b has also been examined in anterior regions during working memory tasks (e.g., Padgaonkar, Zanto, Bollinger, & Gazzaley, 2017).

The goal of the present study was to determine if neural activity during a working memory task differed between monolingual and bilingual younger and older adults. Although a recent meta-analysis reported that bilinguals have a larger WM capacity than monolinguals (Grundy & Timmer, 2017), a population-based study examining over 11,000 participants found no evidence of a bilingual advantage in WM (Nichols et al., 2020). Given the mixed findings in this area, examining the underlying neural activity of WM may provide insight into these inconsistencies. To our knowledge, only one study has examined whether bilingual older adults exhibit enhanced WM capacity and neural activity compared to monolinguals (Morrison & Taler 2020). That study found no behavioral differences between monolinguals and bilinguals during a delayed matching-to-sample task. Bilingual participants exhibited larger P3b and P2 amplitudes and smaller N2 amplitudes than monolinguals, suggesting that compared to monolinguals, bilinguals may have more resources available for task completion and require less effort to discriminate the target from the memory stimulus.

In a previous study, we used ERPs to examine the influence of bilingualism on neural activity in younger adults during an n-back task (Morrison et al., 2018). The current study expands on those findings by using ERP to compare performance on this task in young and older monolingual and bilingual adults[4]. We predicted that bilingual older adults would show enhanced WM functioning compared to monolingual older adults. We further expected that bilinguals would exhibit larger P3b amplitudes compared to monolinguals. Finally, we predicted that older adults would exhibit increased P3b and P2 amplitudes compared to young adults in easier conditions, but that this increased activity would not be present in more difficult conditions (Schneider-Garces et al., 2010).

2. Methods

A total of 145 participants took part in this study. Young adults (aged 18-30) were recruited through word of mouth at the University of Ottawa, and older adults (aged 65+) were recruited

[4] Data from 23 of the monolingual and 21 of the bilingual young adults in the present paper were previously published in Morrison & Taler (2020).

through advertisements at local community centers and word of mouth. A total of thirteen participants were excluded for the following reasons: four participants had noisy ERP signals requiring exclusion of more than 25% of their trials, seven scored less than 50% in the 2-back condition, and two participants revealed after testing that they were fluent in a third language. Analyses thus included 122[5] participants: 32 young adult English monolinguals (25 females), 31 young adult bilinguals (22 females); 30 older adult English monolinguals (21 females), and 29 older adult bilinguals (20 females). All groups were matched based on age and sex with age differences only present between younger and older groups; demographic and neuropsychological test scores are provided in Table 1. This study was approved by the research ethics board at the Bruyère Research Institute; participants provided informed written consent and were compensated $10 per hour.

[5] Data from a subset of these participants (73 out of 122) has been previously published (Morrison, Kamal, & Taler, 2019). In that publication we compared young adults to high- and low-performing older adults. The purpose of the present study was not to examine differences between low and high performers, but rather the influence of bilingualism on ERP response in young and older adults.

Table 1: *Younger and older adult mean (SD) for demographic data and neuropsychological measures.*

	Young Monolingual	Young Bilingual	Older Monolingual	Older Bilingual	Age Effect†	Language Effect‡,	Age* Language Effect§
N (females)	32(25 females)	31(22 females)	30(21 females)	29(20 females)	---	---	---
Age	19.59(2.18)	20.45(2.14)	73.50 (4.53)	71.41(4.20)	---	.57	.68
Education	14.19(1.88)	15.25(1.83)	15.37(2.77)	16.74(3.00)	**.003**	.71	.73
MoCA	28.23(1.45)	28.23(1.72)	27.60(1.52)	27.03(1.48)	**.002**	.33	.32
Digit Span Forward	10.80(2.20)	11.29(2.56)	10.83(2.21)	10.26(2.18)	.24	.91	.21
Digit Span Backward	7.10(1.87)	7.71(2.27)	7.80(2.34)	7.48(1.93)	.54	.71	.23
Letter # Sequencing	11.16(2.08)	12.48(3.08)	10.57(2.12)	9.52(1.58)	**<.001**	.75	**.006**
WCST	4.23(1.09)	4.61(0.88)	3.70(1.31)	3.56(1.45)	**<.001**	.58	.23
Stroop1	112.06(13.26)	110.90(16.34)	99.83(17.89)	89.44(16.51)	**<.001**	.053	.12
Stroop2	80.16(10.41)	78.00(11.71)	67.20(12.86)	59.67(10.55)	**<.001**	**.022**	.20
Stroop3	51.74(10.97)	54.48(11.44)	36.70(8.73)	36.85(6.71)	**<.001**	.42	.47
Stroop1-3	60.32(10.66)	56.41(14.40)	63.13(15.24)	53.00(18.62)	.26	**.011**	.91
Stroop2-3	28.42(9.14)	23.51(8.57)	20.60(10.46)	22.93(10.79)	.44	**.001**	.67
Digit Symbol-Written	65.16(11.78)	63.84(11.45)	44.00(6.79)	42.85(8.40)	**<.001**	.50	.96
Digit Symbol-Oral	70.10(11.29)	75.00(13.87)	51.27(8.74)	50.15(7.17)	**<.001**	.34	.13
BNT-English (/60)	49.19(9.57)	47.68(8.15)	52.33(4.49)	48.63(5.75)	.13	.055	.41
FAS Fluency- English	40.36(9.39)	41.48(13.79)	43.10(11.85)	40.30(9.55)	.71	.69	.35
Animals-English	24.71(.25)	22.77(5.57)	19.20(5.02)	17.48(3.49)	**<.001**	.06	.91
BNT-French (/60)	---	34.85(10.49)	---	41.65(6.91)	.008	---	---
FAS Fluency- French	---	27.19(9.64)	---	35.84(7.56)	**.001**	---	---
Animals-French	---	17.89 (6.46)	---	16.04(5.24)	.26		

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. †Young adults had higher scores on: MoCA, Letter # sequencing, WCST, Stroop1-3, animal fluency and digit symbol written and oral than older adults. ‡Bilinguals performed worse on the Stroop2, but better on the Stroop interference measures. §Bilingual young adults performed higher than monolingual and bilingual older adults and monolingual young adults.

All potential participants completed a health questionnaire to determine eligibility. The questionnaire was designed to exclude participants that had any neurological or psychiatric history, were taking medications that influenced their cognitive functioning or central nervous system, or had suffered any major head injuries. To determine fluency in English and French, participants were also asked to rate their language proficiency in four modalities (listening, speaking, reading, and writing). The participants rated their abilities from one to five, with one meaning “no ability at all” and five meaning “native-like ability”. Monolinguals were included if they rated English at four or five in all modalities. In order to be classified as bilingual, the participant had to rate all modalities at four or five in both languages, with the exception of writing where a rating of three was accepted. Any participant who rated knowledge of a language other than English (monolinguals) or English/French (bilinguals) above a two (“very little ability”) in any modality was excluded. Bilinguals also completed a language history questionnaire to assess their frequency of language usage. We note that thirty-nine of the 62 monolingual participants reported having some French exposure. This exposure occurs as part of the Ontario elementary school curriculum; however, monolinguals never became fluent in French and have low exposure to French. Average language proficiency scores are provided in Table 2; because monolinguals do not have French fluency and communicate exclusively in English, French proficiency scores are not provided for this group.

Table 2: *Relative use of language and self-reported proficiency ratings for young and older adults mean (SD).*

	Young Monolinguals	Young Bilinguals	Older Monolinguals	Older Bilinguals	Age Effect†	Language Effect‡,	Age* Language Effect§
French Age of Acquisition	6.71 (2.51)	4.80(2.97)	14.25(10.53)	5.97(5.40)	**.001**	**.001**	**.007**
French Age of Fluency	----	10.54(3.46)	----	10.03(7.08)	.532	----	----
English Proficiency Rating							
Listening	4.86(0.36)	4.97(0.18)	4.75 (0.45)	4.90(0.18)	.20	.64	.79
Reading	5(0)	4.97(0.18)	4.75(0.45)	4.86(0.35)	**.004**	.51	.24
Speaking	5(0)	4.97(0.18)	4.67(0.49)	4.86(0.35)	**.001**	.20	.07
Writing	4.95(0.22)	4.94(0.25)	4.75(0.45)	4.72(0.45)	**.009**	.78	.95
French Proficiency Rating							
Listening	1.65(0.48)	4.54(0.51)	1.28(0.49)	4.72(0.45)	.26	**<.001**	**.002**
Reading	1.63(0.55)	4.48(0.50)	1.37(0.54)	4.76(0.51)	.93	**<.001**	**.006**
Speaking	1.56(0.50)	4.29(0.51)	1.25(0.47)	4.62(0.56)	.93	**<.001**	**.001**
Writing	1.50(0.50)	3.93(0.68)	1.25(0.47)	4.50(0.50)	.13	**<.001**	**<.001**
French use at home							
Speaking	----	39.17% (40.30)	----	47.72% (36.11)	.43	----	----
Listening to speak	----	40.83% (33.78)	----	45.45% (33.30)	.63	----	----
Reading	----	30.83% (26.82)	----	32.95% (24.86)	.77	----	----
Writing	----	29.17% (26.32)	----	36.36% (30.59)	.37	----	----
French use at school/work:							
Speaking	----	39.17% (26.00)	----	40.91% (23.84)	.81	----	----
Listening to speak	----	41.67% (25.70)	----	42.04% (22.34)	.96	----	----
Reading	----	35.00% (25.93)	----	37.50% (25.29)	.73	----	----
Writing	----	34.17% (25.83)	----	39.77% (22.70)	.42	----	----

Note: Self-rated proficiency was rated on a 5-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. †Young adults self-reported an early age of acquisition, higher ratings on their English reading, speaking, and writing than older adults. Bilingual older adults had higher self-reported French reading, speaking, and writing than young adult bilinguals. ‡Bilinguals reported higher French proficiency in all modalities than monolinguals. §Bilingual older adults reported higher French reading, speaking, and writing abilities than bilingual young adults. Bilinguals reported higher scores in all modalities for French proficiency than monolinguals. Older adult monolinguals reported a later age of acquisition for French than all older groups.

3. Procedure

Participants completed two testing sessions lasting approximately 1.5 to 2 hours each. The first session included an extensive neuropsychological battery to assess general cognitive functioning and language proficiency. The battery included the letter-number sequencing, forward and backward digit span, and written and verbal Digit Symbol Substitution subtests of the Wechsler Adult Intelligence Scale-III (WAIS-III; Wechsler, 1997), the Montreal Cognitive Assessment (Nasreddine et al., 2005), the Stroop task (Stroop, 1935), the Wisconsin Card Sorting Test (Grant & Berg, 1948), verbal fluency (controlled oral word association test: FAS (Borkowski, Benton, & Spreen, 1967) and animal fluency, and the Boston Naming Test (BNT; Kaplan, Goodglass, & Weintraub, 1983). Bilingual participants completed the fluency tasks and BNT in both English and French. During the second session, the participants completed the n-back task (and another unrelated task not reported here)[6] while their EEG, accuracy, and reaction time was recorded.

3.1 N-back task

Participants saw digits one at a time at the center of a computer screen for 1000 ms with an inter-stimulus interval of 1700 ms. The n-back task includes three different memory load conditions. In the 0-back condition, participants pressed the left mouse key in response to the number 0, while in the 1-back condition participants pressed the left mouse key when the number matched the previously seen number (e.g., a 9 and then another 9), and in the 2-back condition, participants pressed the left mouse key when the number matched the one presented two trials previously (e.g., a 9 followed by a 6 and then another 9). Each condition consisted of 180 trials,

[6] The n-back was used as a delay task after an emotional faces paradigm where participants were required to state if a picture was emotionally arousing.

with 60 requiring the participant to respond (by pressing the mouse key). Each condition lasted approximately 10 minutes, for a total of 30 minutes.

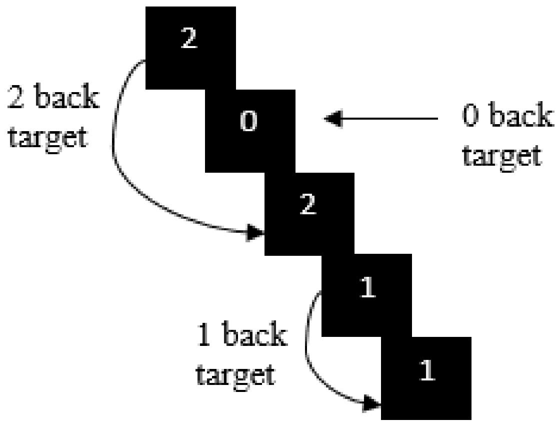

Figure 1: Diagram of the n-back WM task including the 0-back, 1-back, and 2-back conditions.

3.2 EEG data recording and analysis

Electrophysiological data were recorded from 32 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 were recorded by placing an electrode on the infraorbital ridge of the left eye (electrooculography; EOG electrode) and calculated by subtracting the EOG electrode from the electrode immediately above the left eye on the electrode cap (FP1). Horizontal eye movements were calculated by subtracting the activity of electrodes attached to the cap that were placed on the outer edge of the eye. Inter-electrode impedances were kept below 20 kΩ and the EEG was digitized at a rate of 500Hz.

The EEG data were then reconstructed using Brain Products' Analyzer2 software to analyze ERP data (Brain Products, GmbH, Munich, Germany). First, all the channels, including EOG channels, were re-referenced to an average of the two mastoids. The data was then down sampled to 250 Hz and digitally filtered using a low pass filter of 30 Hz and a high pass filter of

0.1 Hz. Visual inspection was completed to identify any channels with high levels of noise that needed to be interpolated with the data from the surrounding sites (Perrin et al., 1989). Due to low levels of noise, interpolation was not completed on any of the sites of interest. Eye blinks and movements obtained through the vertical and horizontal EOG were removed using Independent Components Analysis (Makeig, Bell, & Sejnowski, 1996). The EEG was then constructed into 1200 ms epochs with a 200 ms pre-stimulus baseline period. Epochs containing activity exceeding ±100 μV were rejected from the averaging, with correct trials for both target and non-target trials included in averages.

Three components were selected for analysis: the P2, N2, and P3b. The P2 was measured as the mean amplitude between 125-225 ms. Consistent with previous research, the N2 and P3b occurred later in older adults than younger adults (Daffner et al., 2011; Gajewski & Falkenstein, 2014); therefore we measured this component in different time windows for the two groups. For young adults, the N2 mean amplitude was averaged from 215-340 ms and the P3b amplitude was averaged from 275-475 ms. For older adults, the N2 mean amplitude was averaged from 240-365 ms and the P3b was averaged from 325-525 ms. For all three components, three regions of interest were averaged using the following sites: frontal (F3, Fz, F4), frontocentral (FC1, FCz, FC2), and central (C3, Cz, C4)**.** Three parietal sites were also analyzed (P3, Pz, P4) for the P3b. Frontal, fronto-central, and central regions were analyzed together in a single ANOVA, while parietal regions were analyzed separately. A Greenhouse-Geisser correction procedure was used for all ERP analyses when sphericity was violated (Greenhouse & Geisser, 1959). Bonferroni-corrected pairwise comparisons were performed when comparing groups at the different sites of measurement. For P2 and N2b amplitude and latency and P3b amplitude, separate analyses were run using a 9x3x2x2 mixed model ANOVAs. The within-subject factors were ROI (frontal, frontocentral, central) and Condition (0-, 1-, 2-back), and the between-subjects factors of Group (Monolingual vs. Bilingual) and Age (Young vs. Older). A single mixed ANOVA was also run on the P2 and P3b with the within-subjects factor of Condition (0-, 1-, 2-back) and the between-subjects factors of Group (Monolingual vs. Bilingual) and Age (Young vs. Older) at the parietal ROI.

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 neuropsychological test scores and demographics as the dependent variables (see Table 1 for scores).

4.2 N-back behavioral performance

Trials with reaction times (RTs) exceeding ±2.5 standard deviations from the mean by participant and condition were excluded as outliers (outliers consisted of less than 1% of all trials). Reaction time and accuracy were then analyzed with 3x2x2 mixed ANOVAs with the within-subject factor of Condition (0-, 1-, and 2-back) and between-subjects factor of Language (Monolingual vs. Bilingual) and Age (Young vs. Old). Average accuracy and RTs by group and condition are shown in Table 3.

Older adults had overall slower reaction times than young adults (main effect of Age, $F(1,118)=27.41$, $p<.001$, $\eta^2p=0.19$). Reaction time increased as task difficulty increased (main effect of Condition, $F(2,236)=220.71$, $p<.001$, $\eta^2p=0.65$; with all conditions significantly differing, $p<.001$). Overall accuracy decreased as task difficulty increased (main effect of Condition, $F(2,236)=869.02$, $p<.001$, $\eta^2p=0.88$; with all conditions significantly differing, *p*<.001). Similarly, target accuracy also decreased with increasing task difficulty (main effect of Condition, $F(2,236)=374.21$, $p<.001$, $\eta^2p=0.76$; with all conditions significantly differing, *p*<.001). No main effects or interactions involving language were significant.

Table 3: *Behavioral performance on the n-back working memory task for each condition and group.*

Measures for n-back Mean (Standard Deviation)	Young Monolinguals	Young Bilinguals	Older Monolinguals	Older Bilinguals
0-back				
RT (ms)	386.97(47.83)	382.51(58.89)	442.44(64.12)	415.26(47.08)
Overall Accuracy (%)	98.93(0.66)	98.75(1.23)	99.72(0.56)	98.68(0.76)
Target Accuracy (%)	97.24(1.67)	96.72(3.09)	98.17(3.09)	97.47(1.38)
Omissions (#)	0.13(0.42)	0.42(1.39)	0.13(0.43)	0.24(0.51)
Commissions (#)	0.28(5.22)	0.29(0.64)	0.30(0.70)	0.76(1.18)
1-back				
RT (ms)	444.60(60.33)	447.36(82.66)	496.29(65.91)	475.40(59.30)
Overall Accuracy (%)	97.26(2.71)	98.01(2.85)	97.98(1.35)	97.91(1.32)
Target Accuracy (%)	92.34(8.21)	92.20(8.08)	94.61(3.68)	94.25(4.17)
Omissions (#)	3.06(5.22)	3.35(5.07)	2.00(2.27)	1.93(2.74)
Commissions (#)	0.34(0.60)	1.00(1.31)	0.40(0.67)	0.38(0.62)
2-back				
RT (ms)	497.50(57.08)	479.50(80.48)	580.16(77.93)	549.79(88.74)
Overall Accuracy (%)	86.67(4.91)	87.31(5.23)	86.39(3.61)	86.85(2.62)
Target Accuracy (%)	70.83(16.27)	72.31(17.02)	70.72(10.12)	72.41(8.75)
Omissions (#)	16.90(9.82)	15.48(10.74)	17.27(6.22)	16.03(5.33)
Commissions (#)	6.50(2.91)	6.22(2.39)	6.93(2.89)	7.10(3.13)

Notes: Values given are means with standard deviations. Young adults were overall faster than older adults (main effect of age; *p*<.001), which was the case for all conditions (interaction between Age and Condition, $p \leq .002$).

4.3 ERP results

ERP condition effects collapsed across age and language can be seen in Figure 2. Figure 3 shows the ERP waveforms of monolingual and bilingual participants collapsed across age. ERPs showing the main effect of age collapsed across language are shown in Figure 4.

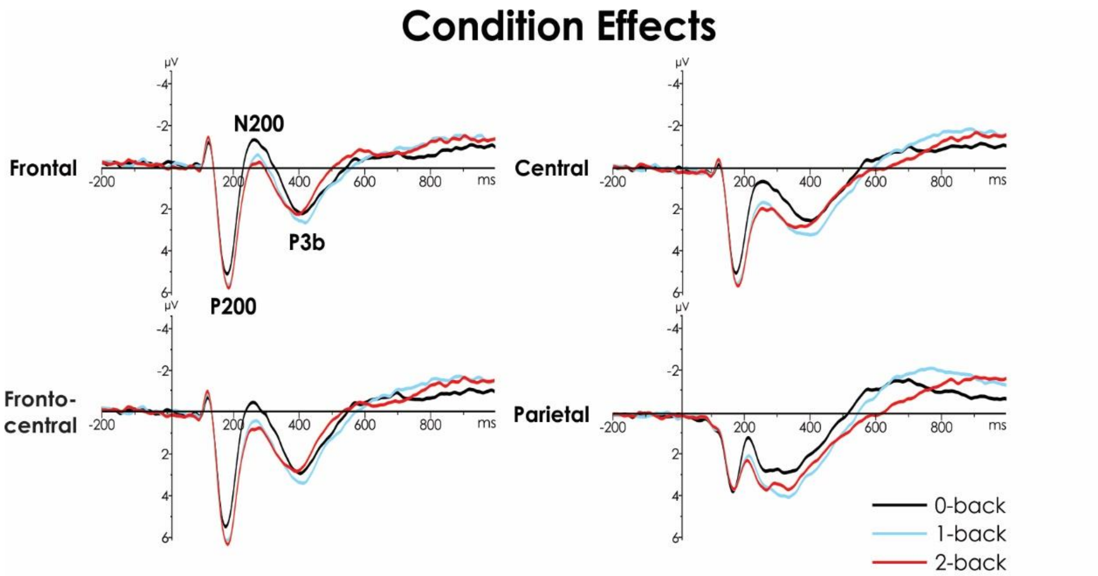

Figure 2: ERP waveforms collapsed across age and language to show the main effect of condition on all components at each region of interest. Averages at frontal (F3, Fz, F4), frontocentral (FC1, FCz, FC2), central (C3, Cz, C4), and parietal (P3, Pz, P4) regions are shown. Negative is plotted upwards.

4.3.1 P2 amplitude

P2 amplitude was analyzed at frontal, frontocentral, and central regions. Across all participants, the 0-back elicited a smaller P2 amplitude than both the 1-back and 2-back (p<.001), (main effect of Condition, F(2,236)=19.47, p<.001, η^2p =0.14). Older adults exhibited larger amplitudes than younger adults in all conditions (interaction between Age and Condition, F(2,236)=10.88, p<.001, η^2p =0.08; p<.001 for all pairwise comparisons). Young adults' P2 amplitude became larger with increasing task difficulty, with all conditions significantly differing ($p\leq$.031). Older adults' P2 amplitude increased from 0-back to 1-back (p=.013) then decreased from 1-back to 2-back (p=.023). No main effects or interactions involving language were significant.

4.3.2 N2 amplitude

The frontal, frontocentral, and central region analysis for the N2 component showed a main effect of Condition, (F(2,236)=19.84, p<.001, η^2p =0.14), with the 0-back eliciting a significantly larger amplitude than the 1-back ($p<.001$) and 2-back ($p<.001$). Young adults exhibited larger N2 amplitudes than older adults during the 1-back condition ($p=.03$; as shown by an Age x Condition interaction, $F(2,236)=4.12$, $p=.021$, $\eta^2p=0.03$). Young adults' N2 amplitude was largest in the 0-back compared to 1-back ($p=.001$) and 2-back ($p<.001$), which did not differ. Similar to the P2, older adults' N2 amplitude increased from 0-back to 1-back ($p<.001$) but then decreased from 1-back to 2-back ($p=.002$). There were no other main effects or interactions involving age or language.

4.3.3 P3b amplitude

The frontal, frontocentral, and central region analysis revealed that the 1-back elicited a larger P3b amplitude than the 0-back ($p<.001$) and 2-back ($p<.001$), which did not differ from each other (main effect of Condition, $F(2,236)=9.12$, $p<.001$, $\eta^2p=0.07$). Older adults exhibited larger overall anterior P3b amplitudes than young adults (main effect of Age, $F(1,118)=7.70$, $p=.006$, $\eta^2p=0.06$). The Age by Condition interaction ($F(2,236)=24.07$, $p<.001$, $\eta^2p=0.17$) showed that older adults had larger amplitudes than young adults in the 0-back ($p<.001$) and 1-back ($p<.001$), but not in the 2-back ($p=.65$). However, when examining the Age by Condition interaction, it is evident that younger and older adults have different patterns as task difficulty increased. Young adults' P3b amplitude continued to increase with task difficulty (with 0-back differing from both 1- and 2-back, $p\leq.020$). On the other hand, older adults' P3b amplitude increased from the 0-back to the 1-back ($p=.020$) but then decreased in amplitude from the 1-back to the 2-back ($p<.001$). Bilinguals exhibited a larger P3b amplitude than monolinguals in frontal, frontocentral, and central regions (main effect of Language, $F(1,118)=5.30$, $p=.02$, $\eta^2p=0.04$). Interactions involving language were not significant.

The P3b parietal analysis revealed a main effect of Condition, $F(2,236)=30.81$, $p<.001$, $\eta^2p=0.21$), with all conditions significantly differing, $p\leq.008$ (amplitude increased from 0- to 1-back and then decreased from 1- to 2-back). Older adults exhibited a smaller amplitude than young adults in only the 2-back ($p=.002$; interaction between Age and Condition, $F(2,236)=17.24$, $p<.001$, $\eta^2p=0.13$). P3b amplitude increased in younger adults with increasing task difficulty (0-back was smaller than 1- and 2-back, $p<.001$). Older adults had increased parietal P3b amplitudes from the 0-back to the 1-back ($p<.001$) and then decreased amplitudes from the 1-back to the 2-back ($p<.001$), with 0-back and 2-back not significantly differing.

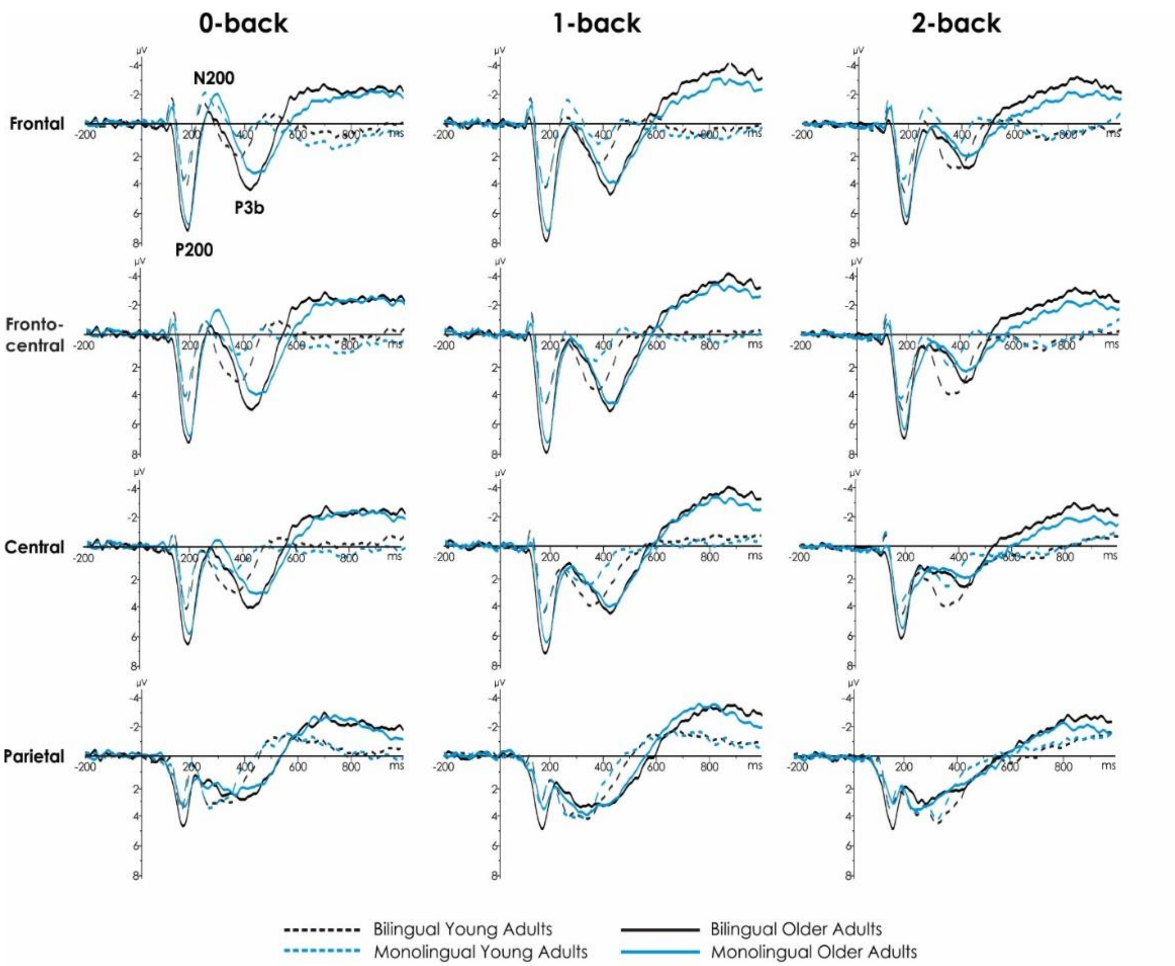

Figure 3: ERP waveforms of monolingual and bilingual younger and older adults. Averages at frontal (F3, Fz, F4), frontocentral (FC1, FCz, FC2), central (C3, Cz, C4), and parietal (P3, Pz, P4) regions are shown. Negative is plotted upwards.

Table 4: *Summary of ERP results.*

ERP component/ description	Condition Effects	Age Effects	Language Effects
P2	0-back < 1- and 2-back *YA:* 0-back < 1-back < 2-back *OA:*1-back > 0- and 2-back	YA < OA in all conditions	n.s.
N2	0-back > 1- and 2-back *YA:* 0-back > 1- and 2-back *OA:* 1-back > 0- and 2-back	YA > OA in 1-back	n.s.
P3b (anterior)	1-back > 0- and 2-back *YA:* 0-back < 1- and 2-back *OA:* 0- and 2-back < 1-back; 0-back > 2-back	YA < OA in 0- and 1-back	Monolinguals < bilinguals
P3b (parietal)	0-back < 2-back < 1-back *YA:*0-back < 1- and 2-back *OA:* 1-back > 0- and 2-back	YA > OA in 2-back	n.s.

Note: Anterior region is an average of frontal, fronto-central, and central regions. Parietal is an average of P3, Pz, & P4.

5.0 Discussion

The current study was designed to determine if ERPs differed between younger and older monolinguals and bilinguals during a WM task. Participants completed an n-back task while their EEG, accuracy, and reaction time were recorded. Much research has been conducted to understand the effect of bilingualism on WM. However, findings have been inconsistent, possibly because most studies include primarily young adult samples and use only behavioral measures. To address these limitations, the present study compared the ERPs of young and older adult monolinguals and bilinguals while they completed an n-back WM task.

Although no behavioral differences were observed between bilinguals and monolinguals, we found that bilinguals exhibited larger P3b amplitudes than monolinguals. Regarding age effects, older adults displayed larger P2 amplitudes than young adults in anterior regions. Older adults also exhibited larger P3b amplitudes during the 0-back and 1-back in anterior regions compared to young adults. In parietal regions, older adults exhibited smaller P3b amplitudes during the 2-back compared to young adults. These findings provide evidence for both age and language group differences during a WM task.

5.1 Behavioral and neuropsychological effects

Both accuracy and reaction time were influenced by increasing task difficulty. Accuracy decreased as WM load increased from 0- to 2-back, whereas reaction time increased with increasing WM load. Monolinguals and bilinguals did not differ in accuracy or reaction time. Although older adults' accuracy was similar to that of young adults, their reaction times were significantly longer than young adults. There was no interaction between age and language for either accuracy or reaction time.

There were no language group differences in executive functioning and working performance in the neuropsychological battery. This finding is consistent with several recent reports indicating no bilingual advantage in cognitive functioning (Dick et al., 2018; Lehtonen, Soveri, Bruin, & Antfolk, 2018; Paap & Greenberg, 2013, Nichols et al., 2020). However, there is evidence that language proficiency, usage, and age of acquisition can influence whether group differences between monolinguals and bilinguals are obtained (e.g., Luk & Bialystok, 2013; Tao, Marzecová, Taft, Asanowicz, & Wodniecka, 2011). Tao et al. (2011) found that, although both early and late bilinguals have more efficient executive networks than monolinguals, bilinguals who were more balanced in proficiency and usage showed the largest cognitive advantage. Similarly, other researchers have reported that more time spent actively using both languages results in greater advantages in cognitive control (Luk, De Sa, & Bialystok, 2011). As shown in

Table 2, the bilingual participants in the present study use their second language only 30-40% of the time, and therefore may exhibit fewer advantages than a bilingual who uses both their languages equally.

Consistent with previous studies (Brockmole & Logie, 2013; Park et al., 2002), we found that older adults had reduced WM capacity compared to younger adults. Lower accuracy was observed for older adults in tasks that test inhibition (as measured by the Stroop task) and processing speed and attention (as measured by the digit symbol test) compared to young adults. We predicted that older adult bilinguals would benefit from the "bilingual advantage" and show better cognitive functioning than older monolinguals. However, our analyses did not reveal any Age by Language interactions to support the hypothesis that bilingualism may help mitigate age-related cognitive decline.

5.2 ERP effects: bilingualism

Despite the two language groups' similar neuropsychological and behavioral performance, we did find differences between monolinguals and bilinguals in the ERP response. Overall, bilingual participants had similar P2 and N2 amplitudes, but larger P3b amplitudes compared to monolinguals. In a previous study examining ERPs in a delayed matching-to-sample task, we found that bilinguals had smaller N2, but larger P2 and P3b amplitudes than monolinguals (Morrison & Taler, 2020).

Although the current P3b results are consistent with our previous findings, the P2 and N2 results differ. The study differences in the N2 and P2 results may reflect differences in the aspects of WM required to complete the tasks. The delayed matching-to-sample task is a span task that requires the use of a phonological loop and articulatory rehearsal to maintain information in WM (Baddeley, 2000; Germano & Kinsella, 2005). The n-back, in contrast, activates many processes simultaneously (e.g., encoding, updating of information, matching the stimulus to the one *n*-times before) (Jaeggi, Buschkuehl, Perrig, & Meier, 2010). The delayed matching-to-sample task may activate components of WM (i.e., the phonological loop) that are more strongly associated with language than the n-back. Accordingly, differences between monolinguals and bilinguals may be task-dependent and only occur under specific conditions.

Consistent with previous research, we observed a larger P3b amplitude in bilinguals compared to monolinguals (e.g., Barac, Moreno, & Bialystok, 2016; Moreno, Wodniecka, Tays, Alain, & Bialystok, 2014).This finding is consistent with the hypothesis that bilinguals show advantages in executive functioning (Barac et al., 2016; Moreno et al., 2014). However, we did not observe behavioral or neuropsychological advantages in bilinguals compared to monolinguals. This lack of difference between monolinguals and bilinguals brings into question whether the increased P3b activity can reliably predict a cognitive advantage. Thus, we cannot exclude the possibility that increased activity in bilinguals may not translate to an advantage but may instead reflect differences in processing. Future research should examine ERP differences between monolinguals and bilinguals under more strenuous task demands.

5.3 Age group ERP effects

Based on the CRUNCH model (Reuter-Lorenz & Lustig, 2005), we predicted that older adults would show larger P3b amplitudes than young adults in the easy tasks (0- and 1-back), but smaller amplitudes during the more difficult task (2-back) (Schneider-Garces et al., 2010). With increased task difficulty, brain activity in older adults typically plateaus because their processing resources have reached maximum capacity in the easier tasks, whereas younger adults' activity will continue to increase with increasing task difficulty. Our results are consistent with this theory: older adults exhibited increased P3b amplitude in the 1-back condition compared to the 0-back condition, but decreased amplitude in the 2-back compared to the 1-back. Furthermore, compared to young adults, older adults had larger overall P3b amplitudes in frontal regions during the 0- and 1-back, and smaller P3b amplitudes in parietal regions during the 2-back. These findings suggest that older adults recruit additional resources at lower levels of task difficulty (as shown by the increased P3b amplitude in the 0- and 1-back conditions). Older adults may exhibit lower amplitudes during the most difficult task (2-back) because they are unable to recruit additional resources at that level of difficulty. During the more difficult task, the older adults' available resources reach ceiling, leading to insufficient processing for this task. However, we did not find a behavioral difference between younger and older adults to support this contention. Future research should replicate this research with a larger group of participants and under more difficult tasks.

Older adults exhibited larger P2 amplitudes than young adults in all frontal, frontocentral, central, and parietal regions. A larger P2 typically reflects enhanced WM processing (Finnigan et al., 2011). However, because older adults did not show increased accuracy during the n-back compared to young adults (and in fact achieved lower scores in the WM task included in the neuropsychological battery), we interpret this increase in amplitude as reflecting a compensatory mechanism. This interpretation is consistent with previous studies observing that older adults exhibit increased activity in parietal (Huang, Polk, Goh, & Park, 2012) and frontal regions (Cabeza et al., 2004) in order to maintain a performance similar to young adults. Previous studies with older adults have shown both decreased (Missonnier et al., 2004) and increased P2 amplitude (McEvoy, Pellouchoud, Smith, & Gevins, 2001) with age. McEovy et al. (2001) did not find performance differences between younger and older adults, whereas Missonnier et al.

(2004) found that older adults had lower performance than young adults. Taken together with our current findings, these results suggest that older adults who maintain similar performance to their young adult counterparts may also show increased activation (i.e., larger P2 amplitudes than young adults). In contrast, decreased activation in older adults (i.e., smaller P2 amplitudes) may be observed when older adults have lower performance than young adults.

It should be noted that in the present study, we interpreted bilinguals' larger P3b amplitudes as reflecting a possible advantage, while older adults' larger P3b amplitudes were interpreted as reflecting a compensatory mechanism. P3b amplitude declines with increasing task difficulty because fewer resources are available for task completion (Polich, 2007). Thus, the larger P3b amplitudes observed in bilinguals compared to monolinguals may suggest increased resources available across all conditions. Older adults displayed larger amplitudes than young adults only during the easier conditions (0-back and 1-back) and smaller P3b amplitudes than young adults in parietal regions during the 2-back. The fact that larger P3b amplitudes were observed in older adults comparted to young adults only during the easier tasks, but not during the more difficult ones, suggests that older adults may need to use additional resources during the easier tasks and as a result do not have enough resources available for task completion during the more difficult task (resulting in decreased activation).

We hypothesized that bilingual older adults would outperform monolingual older adults because bilingualism may reduce the cognitive declines associated with increased age. However, no interaction between age and language was observed in ERP or behavioral measures. Bilinguals and monolinguals exhibited the same performance on behavioral measures. In addition, the language effects observed in the ERP data were the same for younger and older adults. Thus, even though older adult monolinguals and bilinguals exhibited different amplitude

ERP amplitudes their cognitive functioning did not differ. Taken together, the ERP differences between monolinguals and bilinguals may indicate that bilinguals and monolinguals engage different processing and/or strategies for task completion.

6.0 Conclusion

We found that bilinguals exhibited larger P3b amplitudes than monolinguals, suggesting that bilinguals may have additional cognitive resources available for task completion. Neuropsychological and behavioral performance did not differ between the two language groups, suggesting that the additional resources available to bilinguals do not translate to a cognitive advantage in this population. Although we observed ERP differences between monolinguals and bilinguals, no bilingual advantage in behavioral performance was observed. Compared to young adults, older adults exhibited smaller P3b amplitudes during the 2-back, larger P2 amplitudes overall, and larger P3b amplitudes in frontal regions, suggesting that older adults recruit additional brain regions during a WM task to maintain task performance.

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Antón, E., García, Y. F., Carreiras, M., & Duñabeitia, J. A. (2016). Does bilingualism shape inhibitory control in the elderly? *Journal of Memory and Language, 90,* 147-160. https://doi.org/10.1016/j.jml.2016.04.007

Atkins, P. W., & Baddeley, A. D. (1998). Working memory and distributed vocabulary learning. *Applied Psycholinguistics*, *19*(4), 537-552.

Baddeley A (2000) The episodic buffer: a new component of working memory? Trends in *Cognitive Sciences,* 4, 417–423. https://doi.org/10.1016/S1364-6613(00)01538-2

Baddeley, A. (2003). Working memory: looking back and looking forward. *Nature Reviews Neuroscience*, *4*(10), 829-839.

Badzakova-Trajkov, G. (2008). *A behavioural and functional imaging investigation of Stroop task performance in late proficient bilinguals* (Doctoral dissertation, ResearchSpace@ Auckland).

Barac, R., Moreno, S., & Bialystok, E. (2016). Behavioural and electrophysiological differences in executive control between monolingual and bilingual children. *Child Development, 87*(*4*), 1277–1290. DOI: 10.1111/cdev.12538

Bialystok, E., Craik, F. I., & Freedman, M. (2007). Bilingualism as a protection against the onset of symptoms of dementia. *Neuropsychologia*, *45*(2), 459-464. https://doi.org/10.1016/j.neuropsychologia.2006.10.009

Bialystok, E., & Feng, X. (2009). Language proficiency and executive control in proactive interference: Evidence from monolingual and bilingual children and adults. *Brain and Language*, *109*(2-3), 93-100. https://doi.org/10.1016/j.bandl.2008.09.001

Bialystok, E., Martin, M. M., & Viswanathan, M. (2005). Bilingualism across the lifespan: The rise and fall of inhibitory control. *International Journal of Bilingualism, 9*(1), 103-119.

Blom, E., Küntay, A. C., Messer, M., Verhagen, J., & Leseman, P. (2014). The benefits of being bilingual: Working memory in bilingual Turkish–Dutch children. *Journal of Experimental Child Psychology, 128*, 105-119. https://doi.org/10.1016/j.jecp.2014.06.007

Borkowski, J. G., Benton, A. L., & Spreen, O. (1967). Word fluency and brain Damage. *Neuropsychologia*, *5*(2), 135-140

Brockmole, J. R., & Logie, R. H. (2013). Age-related change in visual working memory: a study of 55,753 participants aged 8–75. *Frontiers in Psychology*, 4, 12. https://doi.org/10.3389/fpsyg.2013.00012

Cabeza, R., Daselaar, S. M., Dolcos, F., Prince, S. E., Budde, M., & Nyberg, L. (2004). Task-independent and task-specific age effects on brain activity during working memory, visual attention and episodic retrieval. *Cerebral Cortex*, *14*(4), 364-375.

https://doi.org/10.1093/cercor/bhg133

Christensen, H. (2001). What cognitive changes can be expected with normal ageing? *Australian & New Zealand Journal of Psychiatry*, *35*(6), 768-775. https://doi.org/10.1046/j.1440-1614.2001.00966.x

Chung-Fat-Yim, A., Himel, C., & Bialystok, E. (2019). The impact of bilingualism on executive function in adolescents. *International Journal of Bilingualism*, *23*(6), 1278-1290. https://doi.org/10.1177%2F1367006918781059

Daffner, K. R., Chong, H., Sun, X., Tarbi, E. C., Riis, J. L., McGinnis, S. M., & Holcomb, P. J. (2011). Mechanisms underlying age-and performance-related differences in working memory. *Journal of Cognitive Neuroscience*, *23*(6), 1298-1314. https://dx.doi.org/10.1162%2Fjocn.2010.21540

Dick, A., Garcia, N. L., Pruden, S. M., Thompson, W. K., Hawes, S. W., Sutherland, M. T., ... & Gonzalez, R. (2018). No bilingual advantage for executive function: Evidence from a large sample of children in the Adolescent Brain and Cognitive Development (ABCD) Study. *PsyArXiv. July, 8*.

Engel de Abreu, P. M. (2011). Working memory in multilingual children: Is there a bilingual effect? *Memory*, *19*(5), 529-537. https://doi.org/10.1080/09658211.2011.590504

Finnigan, S., O'Connell, R. G., Cummins, T. D., Broughton, M., & Robertson, I. H. (2011). ERP measures indicate both attention and working memory encoding decrements in aging. *Psychophysiology*, *48*(5), 601-611. DOI: 10.1111/j.1469-8986.2010.01128.x

Fitzgerald, P. G., & Picton, T. W. (1983). Event-related potentials recorded during the discrimination of improbable stimuli. *Biological Psychology*, *17*(4), 241-276. DOI: 10.1016/0301-0511(83)90003-0

Folstein, J. R., & Van Petten, C. (2008). Influence of cognitive control and mismatch on the N2 component of the ERP: a review. *Psychophysiology*, *45*(1), 152-170. https://doi.org/10.1111/j.1469-8986.2007.00602.x

Gajewski, P. D., & Falkenstein, M. (2014). Age-related effects on ERP and oscillatory EEG-dynamics in a 2-back task. *Journal of Psychophysiology*. https://doi.org/10.1027/0269-8803/a000123

Germano, C., & Kinsella, G. J. (2005). Working memory and learning in early Alzheimer's disease. *Neuropsychology Review*, 15(1), 1-10.

Grant, D. A., & Berg, E. (1948). A behavioral analysis of degree of reinforcement and ease of shifting to new responses in a Weigl-type card-sorting problem. *Journal of Experimental Psychology*, *38*(4), 404.

Grundy, J. G., & Timmer, K. (2017). Bilingualism and working memory capacity: A comprehensive meta-analysis. *Second Language Research*, *33*(3), 325-340. https://doi.org/10.1177/0267658316678286

Huang, C. M., Polk, T. A., Goh, J. O., & Park, D. C. (2012). Both left and right posterior parietal activations contribute to compensatory processes in normal aging. *Neuropsychologia*, *50*(1), 55-66. https://doi.org/10.1016/j.neuropsychologia.2011.10.022

Jaeggi, S. M., Buschkuehl, M., Perrig, W. J., & Meier, B. (2010). The concurrent validity of the N-back task as a working memory measure. *Memory*, 18(4), 394-412.

Jodo, E., & Kayama, Y. (1992). Relation of a negative ERP component to response inhibition in a Go/No-go task. *Electroencephalography and Clinical Neurophysiology*, *82*(6), 477-482. https://doi.org/10.1016/0013-4694(92)90054-L

Kaplan, E., Goodglass, H., & Weintraub, S. (1983). The Boston Naming Test. Lea & Febiger. *Philadelphia, PA*.

Kavé, G., Eyal, N., Shorek, A., & Cohen-Mansfield, J. (2008). Multilingualism and cognitive state in the oldest old. *Psychology and Aging, 23*(1), 70. https://doi.org/10.1037/0882-7974.23.1.70

Kok, A. (1998). Is P3 amplitude a suitable measure of processing capacity? *International Journal of Psychophysiology*, *30*(1-2), 67-67. https://doi.org/10.1016/S0167-8760(98)90168-4

Kousaie, S., & Phillips, N. A. (2012). Ageing and bilingualism: Absence of a “bilingual advantage” in Stroop interference in a nonimmigrant sample. *The Quarterly Journal of Experimental Psychology*, *65*(2), 356-369. http://dx.doi.org/10.1080/17470218.2011.604788

Kousaie, S., & Taler, V. (2015). The bilingual advantage: Elusive but worth the effort? *Cortex* 73, 338–339. https://doi.org/10.1016/j.cortex.2015.07.019.

Kudo, M., & Swanson, H. L. (2014). Are there advantages for additive bilinguals in working memory tasks? *Learning and Individual Differences*, *35*, 96-102. https://doi.org/10.1016/j.lindif.2014.07.019

Lehtonen, M., Soveri, A., Laine, A., Järvenpää, J., De Bruin, A., & Antfolk, J. (2018). Is bilingualism associated with enhanced executive functioning in adults? A meta-analytic review. *Psychological Bulletin, 144*(4), 394.

Luk, G. (2015). Who are the bilinguals (and monolinguals)? *Bilingualism: Language and Cognition*, *18*(1), 35-36. http://dx.doi.org/10.1017/S1366728914000625

Luk, G., De Sa, E. R. I. C., & Bialystok, E. (2011). Is there a relation between onset age of bilingualism and enhancement of cognitive control? *Bilingualism: Language and Cognition*, *14*(4), 588-595. doi:10.1017/S1366728911000010

Lukasik, K. M., Lehtonen, M., Soveri, A., Waris, O., Jylkkä, J., & Laine, M. (2018). Bilingualism and working memory performance: Evidence from a large-scale online study. *PloS ONE*, *13*(11). https://dx.doi.org/10.1371%2Fjournal.pone.0205916

McEvoy, L. K., Pellouchoud, E., Smith, M. E., & Gevins, A. (2001). Neurophysiological signals of working memory in normal aging. *Cognitive Brain Research*, *11*(3), 363-376. https://doi.org/10.1016/S0926-6410(01)00009-X

Missonnier, P., Gold, G., Leonards, U., Costa-Fazio, L., Michel, J. P., Ibáñez, V., & Giannakopoulos, P. (2004). Aging and working memory: early deficits in EEG activation of posterior cortical areas. *Journal of Neural Transmission*, *111*(9), 1141-1154.

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

Moreno, S., Wodniecka, Z., Tays, W., Alain, C., & Bialystok, E. (2014). Inhibitory control in bilinguals and musicians: event related potential (ERP) evidence for experience-specific effects. *PloS One*, *9*(4). https://doi.org/10.1371/journal.pone.0094169

Morrison, C., Kamal, F., & Taler, V. (2018). The influence of bilingualism on working memory event-related potentials. *Bilingualism: Language and Cognition*, *22*(1), 191-199. https://doi.org/10.1017/S1366728918000391

Morrison, C., Kamal, F., Le, K., & Taler, V. (2019). Monolinguals and bilinguals respond differently to a delayed matching-to-sample task: an ERP study. *Bilingualism: Language and Cognition*, 1-11. https://doi.org/10.1017/S1366728919000816

Morrison, C., Kamal, F., & Taler, V. (2019). The influence of working memory performance on event-related potentials in young and older adults. *Cognitive Neuroscience*, *10*(3), 117-128. https://doi.org/10.1080/17588928.2019.1570104

Morrison, C., & Taler, V. (2020). ERP measures of the effects of age and bilingualism on working memory performance. Neuropsychologia, 107468.

Nasreddine, Z. S., Phillips, N. A., Bédirian, V., Charbonneau, S., Whitehead, V., Collin, I., ... & Chertkow, H. (2005). The Montreal Cognitive Assessment, MoCA: a brief screening tool for mild cognitive impairment. *Journal of the American Geriatrics Society*, *53*(4), 695-699. https://doi.org/10.1111/j.1532-5415.2005.53221.x

Nichols, E. S., Wild, C. J., Stojanoski, B., Battista, M. E., & Owen, A. M. (2020). Bilingualism Affords No General Cognitive Advantages: A Population Study of Executive Function in 11,000 People. *Psychological Science*, 0956797620903113.

Paap, K. R., & Greenberg, Z. I. (2013). There is no coherent evidence for a bilingual advantage in executive processing. *Cognitive Psychology*, *66*(2), 232-258. https://doi.org/10.1016/j.cogpsych.2012.12.002

Padgaonkar, N. A., Zanto, T. P., Bollinger, J., & Gazzaley, A. (2017). Predictive cues and age-related declines in working memory performance. *Neurobiology of Aging*, *49*, 31–39. https://doi.org/10.1016/j.neurobiolaging.2016.09.002

Park, D. C., Lautenschlager, G., Hedden, T., Davidson, N. S., Smith, A. D., & Smith, P. K. (2002). Models of visuospatial and verbal memory across the adult life span. *Psychology and Aging*, *17*(2), 299. DOI: 10.1037//0882-7974.17.2.299

Patel, S. H., & Azzam, P. N. (2005). Characterization of N200 and P300: selected studies of the event-related potential. *International Journal of Medical Sciences*, *2*(4), 147. https://dx.doi.org/10.7150%2Fijms.2.147

Polich, J. (2007). Updating P300: an integrative theory of P3a and P3b. *Clinical Neurophysiology*, 118(10), 2128-2148. https://doi.org/10.1016/j.clinph.2007.04.019

Prior, A., & Gollan, T. H. (2011). Good language-switchers are good task-switchers: Evidence from Spanish–English and Mandarin–English bilinguals. *Journal of the International Neuropsychological Society*, *17*(4), 682-691. https://doi.org/10.1017/S1355617711000580

Ratiu, I., & Azuma, T. (2015). Working memory capacity: Is there a bilingual advantage? *Journal of Cognitive Psychology*, *27*(1), 1-11. https://doi.org/10.1080/20445911.2014.976226

Reuter-Lorenz, P. A., & Lustig, C. (2005). Brain aging: reorganizing discoveries about the aging mind. *Current Opinion in Neurobiology*, *15*(2), 245-251. https://doi.org/10.1016/j.conb.2005.03.016

Schneider-Garces, N. J., Gordon, B. A., Brumback-Peltz, C. R., Shin, E., Lee, Y., Sutton, B. P., ... & Fabiani, M. (2010). Span, CRUNCH, and beyond: working memory capacity and the aging brain. *Journal of Cognitive Neuroscience*, *22*(4), 655-669. https://doi.org/10.1162/jocn.2009.21230

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, *18*(6), 643.

Tao, L., Marzecová, A., Taft, M., Asanowicz, D., & Wodniecka, Z. (2011). The efficiency of attentional networks in early and late bilinguals: the role of age of acquisition. *Frontiers in Psychology*, *2*, 123. https://doi.org/10.3389/fpsyg.2011.00123

Wechsler, D. (1997). Wechsler Memory Scale (WMS-III). San Antonion: TX:Psychological Corportation.

Part 2: (Paradigm 2) Study 4

Study 4 was published in *Neuropsychologia.* The manuscript is thus formatted in accordance with the requirements of that journals.

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Study 4 was conducted as a follow-up to Study 2 in younger adults. In Study 2, young adult English monolinguals were compared to young adult English-French bilinguals during a delayed matching-to-sample task. Although performance measures were similar, ERP differences were present across groups. Bilinguals exhibited larger P3b amplitudes than monolinguals and smaller N2b amplitudes during retrieval. The young adult ERP differences can be interpreted as young adult bilinguals having more cognitive resources available for task completion than young adult monolinguals. Study 4 was thus was designed to see if these potential additional resources translate to a behavioral advantage in older adults. Study 4 compared the same sample of young adults to a sample of older adult English monolinguals and English-French bilinguals in order to determine whether bilingualism can mitigate the effects of age-related cognitive decline. The older adults who completed this paradigm were similar to that from the n-back paradigm.

Running Head: Effects of age and bilingualism on WM

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

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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 (Dunabeitia 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).

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 overrecruitment. 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., Anton 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 proficiency scores are presented in Table 2). The study received ethical approval from the ethics board at Bruyere Research Institute and the University of Ottawa; participants provided informed written consent before starting the study and were compensated $10 an hour.

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)	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 .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* Effect
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, $*p < .05$, $**p = .005$ 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.

3. Procedure

Participants completed two testing sessions, each lasting 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.

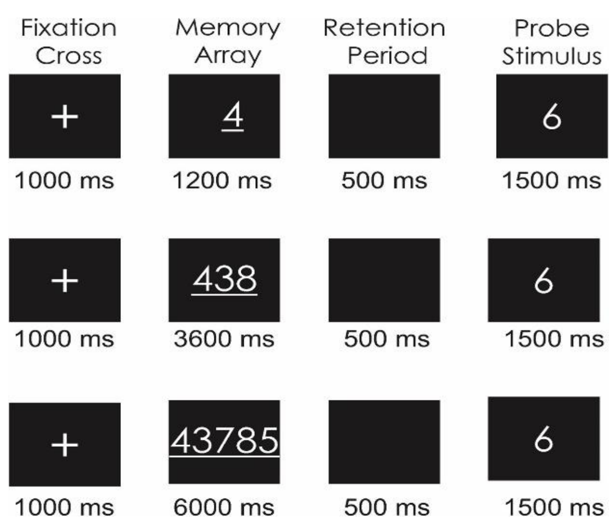

Fig. 1. An example of the stimuli used for each condition and timing of stimulus presentation for the delayed matching-to-sample task. In all examples shown above participants would respond "no" by pressing the "L" key to state that the probe stimulus does not match the memory array.

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). A Greenhouse-Geisser correction procedure was used for all ERP analyses when sphericity was violated (Greenhouse & Geisser, 1959). Bonferroni-corrected pairwise comparisons were performed when comparing groups at the four sites of measurement.

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 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 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) ¼ 34.80, $p < .001$, $n^2_p = .25$). There were no significant main effects or group interactions involving language.

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 ($p = .025$).

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. 2).

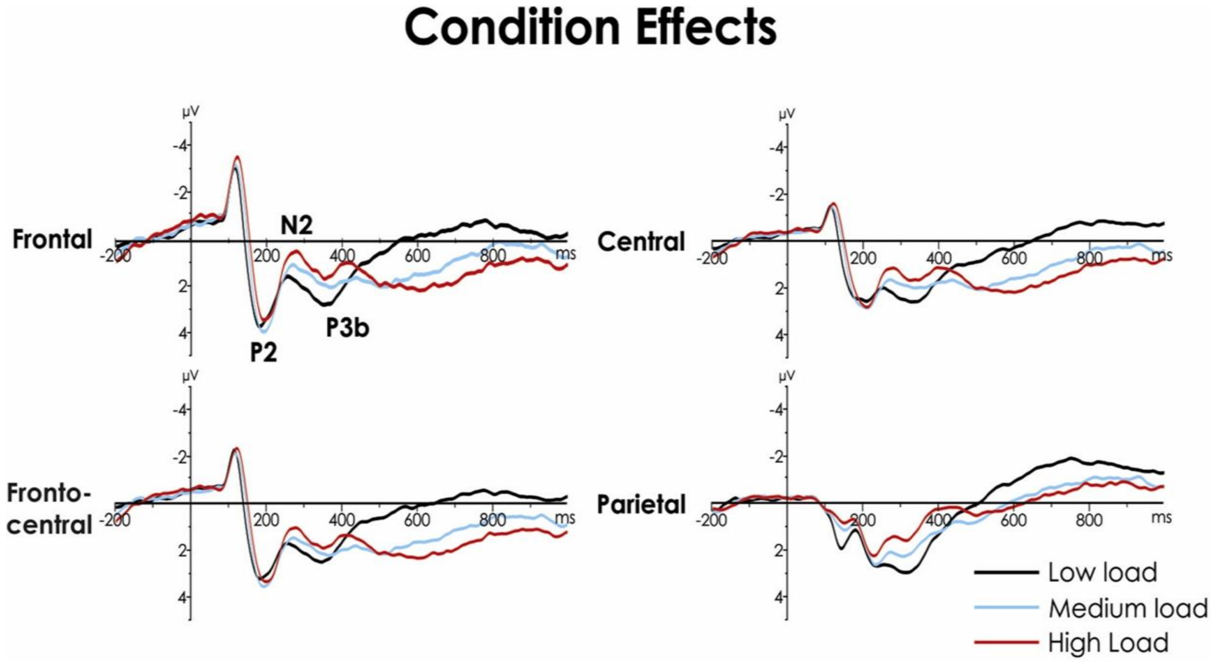

Fig. 2. ERP waveforms collapsed across age and language to show the main effects of condition on all components at each site of interest. Averages at frontal (F3, Fz, F4), fronto-central (FC1, FCz, FC2), central (C3, Cz, C4), and parietal (P3, Pz, P4) regions are shown. Negative is plotted up.

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 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.

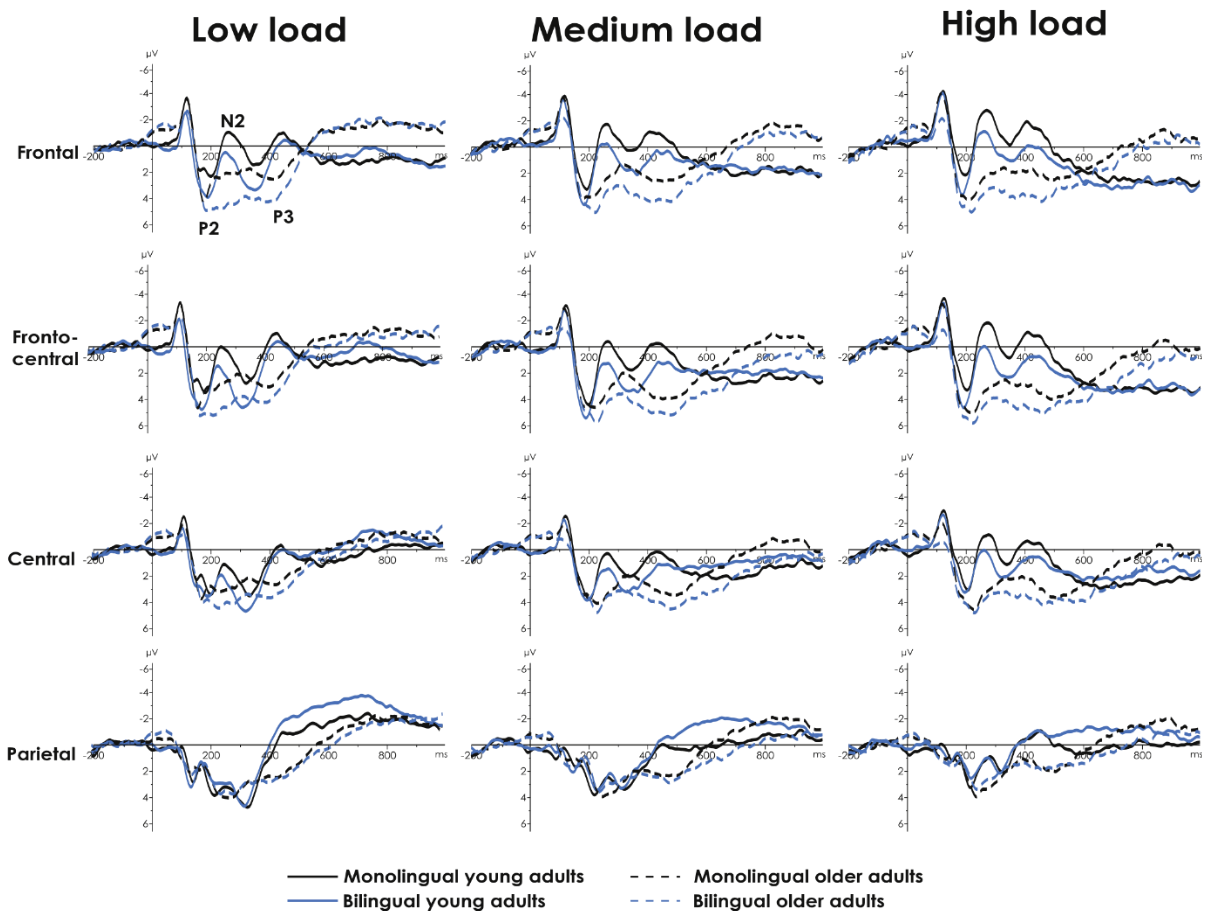

Fig. 3. ERP waveforms displaying young and older monolingual and bilingual adults across conditions at each site of interest. Averages at frontal (F3, Fz, F4), fronto-central (FC1, FCz, Fc2), central (C3, Cz, C4), and parietal (P3, Pz, P4) regions are shown. Negative is plotted up.

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.

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 ¼ medium ¼ 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 ¼ medium ¼ 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 ¼ medium ¼ 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 600þ 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 þ ive with increasing difficulty **Parietal:** More þ ive with increasing difficulty	**Frontal:** OA more -ive then YA **Parietal:** OA more þ ive then YA in low only	**Frontal:** n.s. **Parietal:** n.s.

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

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 present study 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 higher 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.

4.5. 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.

References

Adesope, O.O., Lavin, T., Thompson, T., Ungerleider, C., 2010. A systematic review and meta-analysis of the cognitive correlates of bilingualism. Rev. Educ. Res. 80 (2), 207–245. https://doi.org/10.3102/0034654310368803.

Anderson, N.D., Iidaka, T., Cabeza, R., Kapur, S., McIntosh, A.R., Craik, F.I., 2000. The effects of divided attention on encoding-and retrieval-related brain activity: a PET study of younger and older adults. J. Cognit. Neurosci. 12 (5), 775–792. https://doi. org/10.1162/089892900562598.

Anton, E., García, Y.F., Carreiras, M., Du nabeitia, J.A., 2016. Does bilingualism shape ~ inhibitory control in the elderly? J. Mem. Lang. 90, 147–160. https://doi.org/10.1016/j.jml.2016.04.007.

Baddeley, A., 2012. Working memory: theories, models, and controversies. Annu. Rev. Psychol. 63, 1–29. https://doi.org/10.1146/annurev-psych-120710-100422.

Badzakova-Trajkov, G., 2008. A Behavioural and Functional Imaging Investigation of Stroop Task Performance in Late Proficient Bilinguals. Doctoral dissertation, ResearchSpace@ Auckland.

Bain, B., 1975. Toward an integration of piaget and vygotsky: bilingual considerations. Linguistics 13 (160), 5–20.

Barac, R., Moreno, S., Bialystok, E., 2016. Behavioral and electrophysiological differences in executive control between monolingual and bilingual children. Child Dev. 87 (4), 1277–1290. https://doi.org/10.1111/cdev.12538.

Bennys, K., Portet, F., Touchon, J., Rondouin, G., 2007. Diagnostic value of event-related evoked potentials N200 and P300 subcomponents in early diagnosis of Alzheimer's disease and mild cognitive impairment. J. Clin. Neurophysiol. 24 (5), 405–412. https://doi.org/10.1097/WNP.0b013e31815068d5.

Bialystok, E., Craik, F.I., 2010. Cognitive and linguistic processing in the bilingual mind. Curr. Dir. Psychol. Sci. 19 (1), 19–23. https://doi.org/10.1177/0963721409358571.

Bialystok, E., Craik, F., Luk, G., 2008. Cognitive control and lexical access in younger and older bilinguals. J. Exp. Psychol. Learn. Mem. Cognit. 34 (4), 859. https://doi.org/10.1037/0278-7393.34.4.859.

Bialystok, E., Martin, M.M., Viswanathan, M., 2005. Bilingualism across the lifespan: the rise and fall of inhibitory control. Int. J. BiLing. 9 (1), 103–119. https://doi.org/10.1177/13670069050090010701.

Blom, E., Küntay, A.C., Messer, M., Verhagen, J., Leseman, P., 2014. The benefits of being bilingual: working memory in bilingual Turkish–Dutch children. J. Exp. Child Psychol. 128, 105–119. https://doi.org/10.1016/j.jecp.2014.06.007.

Bonifacci, P., Giombini, L., Bellocchi, S., Contento, S., 2011. Speed of processing, anticipation, inhibition and working memory in bilinguals. Dev. Sci. 14 (2), 256–269. https://doi.org/10.1111/j.1467-7687.2010.00974.x.

Bopp, K.L., Verhaeghen, P., 2005. Aging and verbal memory span: a meta-analysis. J. Gerontol. B Psychol. Sci. Soc. Sci. 60 (5), P223–P233. https://doi.org/10.1093/geronb/60.5.P223.

Borkowski, J.G., Benton, A.L., Spreen, O., 1967. Word fluency and brain Damage. Neuropsychologia 5 (2), 135–140.

Brockmole, J.R., Logie, R.H., 2013. Age-related change in visual working memory: a study of 55,753 participants aged 8-75. Front. Psychol. 4 (JAN), 1–5. https://doi.org/10.3389/fpsyg.2013.00012.

Cabeza, R., Daselaar, S.M., Dolcos, F., Prince, S.E., Budde, M., Nyberg, L., 2004. Task-independent and task-specific age effects on brain activity during working memory, visual attention and episodic retrieval. Cerebr. Cortex 14 (4), 364–375. https://doi.org/10.1093/cercor/bhg133.

Carlson, S.M., Meltzoff, A.N., 2008. Bilingual experience and executive functioning in young children. Dev. Sci. 11 (2), 282–298. https://doi.org/10.1111/j.1467-687.2008.00675.x.Bilingual.

Costa, A., 2005. Lexical access in bilingual production. In: Kroll, J.F., AMB de Groot (Eds.), Handbook of Bilingualism: Psycholinguistic Approaches.

Daffner, K.R., Chong, H., Sun, X., Tarbi, E.C., Riis, J.L., McGinnis, S.M., Holcomb, P.J., 2011. Mechanisms underlying age-and performance-related differences in working memory. J. Cognit. Neurosci. 23 (6), 1298–1314. https://doi.org/10.1162/ jocn.2010.21540.Mechanisms.

Davis, S.W., Dennis, N.A., Daselaar, S.M., Fleck, M.S., Cabeza, R., 2007. Que PASA? The posterior–anterior shift in aging. Cerebr. Cortex 18 (5), 1201–1209. https://doi.org/10.1093/cercor/bhm155.Qu.

Dennis, N.A., Daselaar, S., Cabeza, R., 2007. Effects of aging on transient and sustained successful memory encoding activity. Neurobiol. Aging 28 (11), 1749–1758. https://doi.org/10.1016/j.neurobiolaging.2006.07.006.

Dunabeitia, J.A., Hern~ andez, J.A., Ant on, E., Macizo, P., Estevez, A., Fuentes, L.J., Carreiras, M., 2014. The inhibitory advantage in bilingual children revisited. Exp.Psychol. https://doi.org/10.1027/1618-3169/a000243.

Engel de Abreu, P.M., 2011. Working memory in multilingual children: is there a bilingual effect? Memory 19 (5), 529–537. https://doi.org/10.1080/ 09658211.2011.590504.

Finnigan, S., O'Connell, R.G., Cummins, T.D., Broughton, M., Robertson, I.H., 2011. ERP measures indicate both attention and working memory encoding decrements in aging. Psychophysiology 48 (5), 601–611. https://doi.org/10.1111/j.1469- 8986.2010.01128.x.

Fitzgerald, P.G., Picton, T.W., 1983. Event-related potentials recorded during the discrimination of improbable stimuli. Biol. Psychol. 17 (4), 241–276.

Folstein, J.R., Van Petten, C., 2008. Influence of cognitive control and mismatch on the N2 component of the ERP: a review. Psychophysiology 45 (1), 152–170. https://doi.org/10.1111/j.1469-8986.2007.00602.x.

Friedman, D., 1984. P300 and slow wave: the effects of reaction time quartile. Biol.Psychol. 18 (1), 49–71. https://doi.org/10.1016/0301-0511(84)90028-0.

Fujiyama, H., Garry, M.I., Martin, F.H., Summers, J.J., 2010. An ERP study of age-related differences in the central cost of interlimb coordination. Psychophysiology 47 (3), 501–511. https://doi.org/10.1111/j.1469-8986.2009.00954.x.

Gajewski, P.D., Falkenstein, M., 2014. Age-related effects on ERP and oscillatory EEG-dynamics in a 2-back task. J. Psychophysiol. 28 (3), 162–177. https://doi.org/ 10.1027/0269-8803/a000123.

Gathercole, V.C.M., Thomas, E.M., Kennedy, I., Prys, C., Young, N., Vinas-Guasch, N., ~ et al., 2014. Does language dominance affect cognitive performance in bilinguals? Lifespan evidence from preschoolers through older adults on card sorting, Simon, and metalinguistic tasks. Front. Psychol. 5, 11. https://doi.org/10.3389/ fpsyg.2014.00011.

Goldman, M.C., Negen, J., Sarnecka, B.W., 2014. Are bilingual children better at ignoring perceptually misleading information? A novel test. Dev. Sci. 17 (6), 956–964. https://doi.org/10.1111/desc.12175.

Grant, D.A., Berg, E., 1948. A behavioral analysis of degree of reinforcement and ease of shifting to new responses in a Weigl-type card-sorting problem. J. Exp. Psychol. 38 (4), 404.

Grundy, J.G., Timmer, K., 2017. Bilingualism and working memory capacity: a comprehensive meta-analysis. Sec. Lang. Res. 33 (3), 325–340. https://doi.org/ 10.1177/0267658316678286.

Gutchess, A.H., Welsh, R.C., Hedden, T., Bangert, A., Minear, M., Liu, L.L., Park, D.C., 2005. Aging and the neural correlates of successful picture encoding: frontal activations compensate for decreased medial-temporal activity. J. Cognit. Neurosci. 17 (1), 84–96. https://doi.org/10.1162/0898929052880048.

Jodo, E., Kayama, Y., 1992. Relation of a negative ERP component to response inhibition in a Go/No-go task. Electroencephalogr. Clin. Neurophysiol. 82 (6), 477–482. https://doi.org/10.1016/0013-4694(92)90054-L.

Kane, M.J., Bleckley, M.K., Conway, A.R., Engle, R.W., 2001. A controlled-attention view of working-memory capacity. J. Exp. Psychol. Gen. 130 (2), 169.

Kaplan, E., Goodglass, H., Weintraub, S., 1983. The Boston Naming Test. Lea & Febiger, Philadelphia, PA.

Kessler, C., Quinn, M.E., 1987. Language minority children's linguistic and cognitive creativity. J. Multiling. Multicult. Dev. 8 (1–2), 173–186. https://doi.org/10.1080/ 01434632.1987.9994284.

Kok, A., 2001. On the utility of P3 amplitude as a measure of processing capacity. Psychophysiology 38 (3), 557–577. https://doi.org/10.1016/S0167-8760(98) 90168-4.

Kousaie, S., Phillips, N.A., 2012a. Ageing and bilingualism: absence of a "bilingual advantage" in Stroop interference in a nonimmigrant sample. Q. J. Exp. Psychol. 65 (2), 356–369. https://doi.org/10.1080/17470218.2011.604788.

Kousaie, S., Phillips, N.A., 2012b. Conflict monitoring and resolution: are two languages better than one? Evidence from reaction time and event-related brain potentials. Brain Res. 1446, 71–90. https://doi.org/10.1016/j.brainres.2012.01.052.

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

Kudo, M., Swanson, H.L., 2014. Are there advantages for additive bilinguals in working memory tasks? Learn. Indiv Differ 35, 96–102. https://doi.org/10.1016/j.lindif.2014.07.019.

Lehtonen, M., Soveri, A., Bruin, A. De, Antfolk, J., 2018. Is bilingualism associated with enhanced executive functioning in adults? A Meta-Anal. Rev. 144 (4), 394–425. https://psycnet.apa.org/doi/10.1037/bul0000142.

Li, B.Y., Tang, H.D., Chen, S.D., 2016. Retrieval deficiency in brain activity of working memory in amnesic mild cognitive impairment patients: a brain event-related potentials study. Front. Aging Neurosci. 8, 54. https://doi.org/10.3389/ fnagi.2016.00054.

Lijffijt, M., Lane, S.D., Meier, S.L., Boutros, N.N., Burroughs, S., Steinberg, J.L., et al., 2009. P50, N100, and P200 sensory gating: relationships with behavioral inhibition, attention, and working memory. Psychophysiology 46 (5), 1059–1068. https://doi. org/10.1111/j.1469-8986.2009.00845.x.P50.

Luck, S.J., Woodman, G.F., Vogel, E.K., 2000. Event-related potential studies of attention. Trends Cognit. Sci. 4 (11), 432–440. https://doi.org/10.1016/s1364-6613 (00)01545-x.

Linck, J.A, Osthus, P, Koeth, J.T., Bunting, M.F., 2014. Working memory and second language comprehension and production: A meta-analysis. Psychon. Bull. Rev. 21 (4), 861–883. https://doi.org/10.3758/s13423-013-0565-2.

Luck, S., 2014. An Introduction to the Event-Related Potential Technique. The MIT Press, Cambridge, MA.

Makeig, S., Bell, A.J., Jung, T.P., Sejnowski, T.J., 1996. Independent component analysis of electroencephalographic data. Advances in Neural Information Processing Systems, pp. 145–151.

McEvoy, L.K., Pellouchoud, E., Smith, M.E., Gevins, A., 2001. Neurophysiological signals of working memory in normal aging. Cognit. Brain Res. 11 (3), 363–376. https://doi.org/10.1016/S0926-6410(01)00009-X.

Mertens, R., Polich, J., 1997. P300 from a single-stimulus paradigm: passive versus active tasks and stimulus modality. Electroencephalogr. Clin. Neurophysiology Evoked Potentials Sect. 104 (6), 488–497. https://doi.org/10.1016/S0168-5597(97)00041- 5.

Morales, J., Calvo, A., Bialystok, E., 2013. Working memory development in monolingual and bilingual children. J. Exp. Child Psychol. 114 (2), 187–202. https://doi.org/10.1016/j.jecp.2012.09.002.

Moreno, S., Wodniecka, Z., Tays, W., Alain, C., Bialystok, E., 2014. Inhibitory control in bilinguals and musicians: event related potential (ERP) evidence for experience- specific effects. PloS One 9 (4), 1–8. https://doi.org/10.1371/journal.pone.0094169.

Morrison, C., Kamal, F., Taler, V., 2018. The influence of bilingualism on working memory event-related potentials. Biling. Lang. Cognit. 22 (1), 191–199. https://doi.org/10.1017/S1366728918000391.

Morrison, C., Kamal, F., Le, K., Taler, V., 2019. Monolinguals and bilinguals respond differently to a delayed matching-to-sample task: an ERP study. Biling. Lang. Cognit. 1–11. https://doi.org/10.1017/S1366728919000816.

Nasreddine, Z.S., Phillips, N.A., Bedirian, V., Charbonneau, S., Whitehead, V., Collin, I., et al., 2005. The Montreal Cognitive Assessment, MoCA: a brief screening tool for mild cognitive impairment. J. Am. Geriatr. Soc. 53 (4), 695–699. https://doi.org/10.1111/j.15325415.2005.53221.x.

Nyberg, L., Dahlin, E., Stigsdotter Neely, A., Backman, L., 2009. Neural correlates of € variable working memory load across adult age and skill: dissociative patterns within the fronto-parietal network. Scand. J. Psychol. 50 (1), 41–46. https://doi.org/ 10.1111/j.1467-9450.2008.00678.x.

O'Connell, R.G., Balsters, J.H., Kilcullen, S.M., Campbell, W., Bokde, A.W., Lai, R., et al., 2012. A simultaneous ERP/fMRI investigation of the P300 aging effect. Neurobiol. Aging 33 (10), 2448–2461. https://doi.org/10.1016/j.neurobiolaging.2011.12.021.

Paap, K.R., Greenberg, Z.I., 2013. There is no coherent evidence for a bilingual advantage in executive processing. Cognit. Psychol. 66 (2), 232–258. https://doi.org/10.1016/j.cogpsych.2012.12.002.

Padgaonkar, N.A., Zanto, T.P., Bollinger, J., Gazzaley, A., 2017. Predictive cues and age- related declines in working memory performance. Neurobiol. Aging 49, 31–39.

Park, D.C., Lautenschlager, G., Hedden, T., Davidson, N.S., Smith, A.D., Smith, P.K., 2002. Models of visuospatial and verbal memory across the adult life span. Psychol.Aging 17 (2), 299. https://doi.org/10.1037/0882-7974.17.2.299.

Patel, S.H., Azzam, P.N., 2005. Characterization of N200 and P300: selected studies of the event-related potential. Int. J. Med. Sci. 2 (4), 147. https://doi.org/10.7150/ ijms.2.147.

Payer, D., Marshuetz, C., Sutton, B., Hebrank, A., Welsh, R.C., Park, D.C., 2006. Decreased neural specialization in old adults on a working memory task. Neuroreport 17 (5), 487–491. https://doi.org/10.1097/01. wnr.0000209005.40481.31.

Peal, E., Lambert, W.E., 1962. The relation of bilingualism to intelligence. Psychol. Monogr.: Gen. and Appl. 76 (27), 1.

Perrin, F., Pernier, J., Bertrand, O., Echallier, J.F., 1989. Spherical splines for scalp potential and current density mapping. Electroencephalogr. Clin. Neurophysiol. 72

(2), 184–187.

Pinal, D., Zurron, M., Díaz, F., 2014. Effects of load and maintenance duration on the time course of information encoding and retrieval in working memory: from perceptual analysis to post-categorization processes. Front. Hum. Neurosci. 8, 165. https://doi.org/10.3389/fnhum.2014.00165.

Podell, J.E., Sambataro, F., Murty, V.P., Emery, M.R., Tong, Y., Das, S., et al., 2012. Neurophysiological correlates of age-related changes in working memory updating. Neuroimage 62 (3), 2151–2160. https://doi.org/10.1016/j. neuroimage.2012.05.066.

Polich, J., 2004. Clinical application of the P300 event-related brain potential. Phys. Med. Rehabil. Clin. 15 (1), 133–161. https://doi.org/10.1016/S1047-9651(03) 00109-8.

Polich, J., 2007. Updating P300: an integrative theory of P3a and P3b. Clin. Neurophysiol. 118 (10), 2128–2148. https://doi.org/10.1016/j.clinph.2007.04.019.

Prior, A., Gollan, T.H., 2011. Good language-switchers are good task-switchers: evidence from Spanish–English and Mandarin–English bilinguals. J. Int. Neuropsychol. Soc.17 (4), 682–691. https://doi.org/10.1017/S1355617711000580.

Ratiu, I., Azuma, T., 2015. Working memory capacity : is there a bilingual advantage ? J. Cognit. Psychol. 27 (1), 1–11. https://doi.org/10.1080/20445911.2014.976226.

Reuter-Lorenz, P.A., Lustig, C., 2005. Brain aging:Reorganizing discoveries about the aging mind. Curr. Opin. Neurobiol. 15 (2), 245–251.

Rosselli, M., Ardila, A., Santisi, M.N., Arecco, M.D.R., Salvatierra, J., Conde, A., Lenis, B., 2002. Stroop effect in Spanish–English bilinguals. J. Int. Neuropsychol. Soc. 8 (6), 819–827. https://doi.org/10.1017/S1355617702860106.

Rypma, B., D'Esposito, M., 2000. Isolating the neural mechanisms of age-related changes in human working memory. Nat. Neurosci. 3 (5), 509. https://doi.org/10.1038/ 74889.

Saliasi, E., Geerligs, L., Lorist, M.M., Maurits, N.M., 2013. The relationship between P3 amplitude and working memory performance differs in young and older adults. PloS One 8 (5), e63701. https://doi.org/10.1371/journal.pone.0063701.

Schneider-Garces, N.J., Gordon, B.A., Brumback-Peltz, C.R., Shin, E., Lee, Y., Sutton, B. P., et al., 2010. Span, CRUNCH, and beyond: working memory capacity and the aging brain. J. Cognit. Neurosci. 22 (4), 655–669. https://doi.org/10.1162/ jocn.2009.21230.Span.

Stebbins, G.T., Carrillo, M.C., Dorfman, J., Dirksen, C., Desmond, J.E., Turner, D.A., et al., 2002. Aging effects on memory encoding in the frontal lobes. Psychol. Aging 17 (1), 44. https://doi.org/10.1037/0882-7974.17.1.44.

Stroop, J.R., 1935. Studies of interference in serial verbal reactions. J. Exp. Psychol. 18 (6), 643.

Sullivan, M.D., Janus, M., Moreno, S., Astheimer, L., Bialystok, E., 2014. Early stage second-language learning improves executive control: evidence from ERP. Brain Lang. 139, 84–98. https://doi.org/10.1016/j.bandl.2014.10.004.

Unsworth, N., Spillers, G.J., 2010. Working memory capacity: attention control, secondary memory, or both? A direct test of the dual-component model. J. Mem. Lang. 62 (4), 392–406. https://doi.org/10.1016/j.jml.2010.02.001.

Vallesi, A., 2011. Targets and non-targets in the aging brain: a go/nogo event-related potential study. Neurosci. Lett. 487 (3), 313–317. https://doi.org/10.1016/j. neulet.2010.10.046.

Wechsler, D., 1997. Wechsler Memory Scale (WMS-III). Psychological Corportation, San Antonion: TX.

Zunini, R.A.L., Morrison, C., Kousaie, S., Taler, V., 2019. Task switching and bilingualism in young and older adults: a behavioral and electrophysiological investigation. Neuropsychologia 133, 107186. https://doi.org/10.1016/j. neuropsychologia.2019.107186.

Part 3: (Paradigms 1 & 2) Study 5

Study 5 is in the final editing stages to be submitted to *Neuropsychologia* and is formatted in accordance with the requirements of that journal.

Morrison, C., & Taler, V. ERP differences in working memory between English monolinguals, English-French bilinguals, and Arabic-English bilinguals

Study 5 was conducted as a follow-up to Study 1 and Study 2. In Study 1, young adult English monolinguals were compared to English-French bilinguals during the n-back task. Groups did not differ in accuracy or reaction time. Nevertheless, monolinguals exhibited smaller P3b amplitudes relative to bilinguals. In Study 2, young adult English monolinguals and English-French bilinguals completed the delayed matching-to-sample task. Similar to the n-back results, performance measures did not differ in the delayed matching-to-sample task. On the other hand, bilinguals exhibited larger P3b amplitudes than monolinguals, and smaller N2b amplitudes during retrieval. Study 5 was designed because most studies examining the influence of bilingualism on cognitive functioning focus on languages that are linguistically similar (i.e., small linguistic distance between the languages). Thus, the present study used ERP methodology to determine if there are differences in cognitive processing between English monolinguals, English-French bilinguals, and Arabic-English bilinguals during working memory tasks.

Full title: ERP differences in working memory between English monolinguals, English-French bilinguals, and Arabic-English bilinguals

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Abstract

Research has suggested that being bilingual affords benefits to certain aspects of cognitive functioning relative to being monolingual. Inconsistent findings may be because of methodological limitations within and across studies. One major limitation is that many studies focus on comparing Indo-European languages such as English and French and do not examine linguistic distance. The present study used electroencephalography (EEG) to compare working memory performance and the underlying brain activity between English monolinguals, English-French bilinguals, and Arabic-English bilinguals. Participants completed n-back and delayed matching-to-sample tasks while EEG was recorded. Group differences in event-related potentials (ERPs) were observed in the absence of behavioral differences. In the delayed matching-to-sample task, monolinguals exhibited smaller N2 amplitudes compared to both bilingual groups, and smaller P3b amplitudes compared to English-French bilinguals. In the n-back, English-French bilinguals displayed larger P3b amplitudes than both English monolinguals and Arabic-English bilinguals. P3b amplitude did not differ between Arabic-English bilinguals and monolinguals in either task. Larger P3b amplitudes in the English-French bilinguals may indicate this group uses different processing or cognitive strategies for task completion. Smaller N2 amplitudes in monolinguals compared to both bilingual groups during the delayed matching-to-sample task, suggests increased effort needed for task completion. These results suggest that conflicting findings across bilingualism studies may be due in part to the linguistic distance between the languages under study. Another possibility is that differences between monolinguals and bilinguals are task-dependent.

Keywords: working memory, ERPs, Arabic-English bilinguals, English-French bilinguals, English monolinguals

1. Introduction

Recently, there has been an increase in research examining the effects of bilingualism on cognitive functioning. Bilinguals may display observable cognitive advantages because of either their enhanced conflict monitoring and/or inhibition abilities compared to monolinguals. These enhanced skills occur because bilinguals are constantly managing and switching between two languages and inhibiting the non-relevant language when using the other (for a review see Duñabeitia et al., 2013). Researchers typically observe the bilingual advantage in terms of bilinguals' superiority in performance (i.e., improved accuracy and reaction time) relative to monolinguals on a variety of executive function tasks.

The hypothesis that bilinguals display cognitive advantages over monolinguals has been a topic of debate for several decades. Several studies have reported a bilingual advantage in inhibitory functioning (Bialystok et al., 2008; Carlson & Meltzoff, 2008), executive control (Badzakova-Trajkov, 2008; Prior & Gollan, 2011), cognitive control (Kousaie & Phillips, 2017), and task switching (López Zunini et al., 2019). Not all researchers have been able to replicate findings of a bilingual advantage (e.g., Nichols, Wild, Stojanoski, Battista, & Owen, 2020; Blom et al., 2014; Gathercole et al., 2014; Goldman et al., 2014; Kousaie et al., 2014; Paap and Greenberg, 2013). Some studies suggest that these inconsistencies represent a publication bias, favoring the publication of studies showing a bilingual advantage (de Bruin et al., 2015). One meta-analysis did, however, find an association between bilingualism and working memory even after controlling for publication bias (Linck et al., 2014).

Working memory is the cognitive process involved with manipulating and temporarily storing information in memory for short periods (Baddeley, 2003). Everyday events such as having a conversation, learning, problem-solving, attention, and the ability to selectively ignore information rely on working memory (Alloway & Alloway, 2010; Swanson & Beebe-

Frankenberger, 2004). Early research observed the relationship between working memory and second language acquisition (Atkins & Baddeley, 1998; Baddeley, Gathercole, & Papagno, 1998). Therefore, given the association of working memory to other executive functions and language acquisition, it is an important process to further examine when studying the potential advantages of bilingualism. Inconsistencies have also been found when examining working memory differences between monolinguals and bilinguals. Some findings show advantages in bilinguals compared to monolinguals (Grundy & Timmer, 2017; Kudo & Swanson, 2014; Morales et al., 2013) while others report no group differences (Blom et al., 2014; Lukasik et al., 2018; Ratiu & Azuma, 2015). These failures of replication may be because of linguistic distance between the languages (i.e., how similar are the bilingual's L1 and L2) and a lack of sensitivity in measurement tools.

Languages are organized and grouped based on the ancestral language they are derived from. The branch to which each language is assigned will share the same ancestral language as the other languages on that branch; this grouping is termed a *language family*. For example, the parent language Indo-European has several branches consisting of 445 languages (Eberhard et al., 2020). Languages that are part of the same family smaller linguistic distance because they share lexical, grammatical, and vocabulary similarities (Rowe and Levine 2015). Many bilingualism studies compare languages which are derived from the same parent language (i.e., are part of the same language family). Researchers commonly compare English monolinguals to English bilinguals with another L2 such as Spanish (e.g., Kovelman et al., 2008; Lee Salvatierra & Rosselli, 2011), Welsh (e.g., Wu & Thierry, 2013), and French (e.g., Kousaie & Phillips, 2017; López Zunini et al., 2019). Other studies have examined the effects of bilingualism on other languages that are part of the Indo-European family but reside on different branches such as Italian vs. German (Abutalebi et al., 2012) and Spanish vs Catalan (Burgaleta et al., 2016)

English and French are both derived from the Indo-European family, and therefore lexically resemble one another (García & De Souza, 2014). On the other hand, Arabic is from the Afro-Asiatic family and thus does not share many similarities with English and French. Therefore, Arabic and English have a larger linguistic distance (i.e., larger dissimilarity between languages) than English and French. One of the main differences between English and Arabic is morphological differences; that is, how words are formed in each language. Arabic word formation combines a lexical root, pattern morpheme, and inflectional affix (Ryding, 2014). Affixes are inserted into a word stem following a pattern in a non-linear sequence. A common example of this language structure is using the root "K-T-B", which represents the concept of writing. When combined with the word pattern "maCCaCa" the word generated is *maktaba* or place of writing (Verseteegh, 2014). In English and French, words are generated by putting two morphemes together (Brinton and Brinton 2010; Fejzo, 2016). For example, English and French often use prefixes and suffixes attached to either the beginning or end of a word stem to form either a new word or a new form of the same word (e.g., happy can become unhappy or happiness). Arabic-English bilinguals may exhibit enhanced cognitive functioning compared to English-French bilinguals because Arabic bilinguals may require more cognitive resources to maintain two lexically dissimilar languages.

In bilingualism research, few studies have examined if linguistic distance influences whether a bilingual advantage is observed (Bialystok et al., 2005; Sörman, Hansson, & Ljungberg, 2019; Wierzbicki 2013). These studies compared Swedish-Finnish to Swedish-English (Sörman et al., 2019), Cantonese-English to French-English and English monolinguals

(Bialystok, Craik, et al., 2005), and English monolinguals to English-German and English-Chinese bilinguals (Wierzbicki, 2013). Two of these studies observed that increased linguistic distance leads to bilingual advantages in some tasks (Bialystok et al., 2005; Wierzbicki, 2013). Sörman et al. (2019) studied Finnish and Swedish bilinguals, however, they did not find any impact of linguistic distance on the cognitive processes among bilinguals. Differences may not have been observed because Finnish and Swedish have many loan-words. To our knowledge, only one study has compared English monolinguals to Arabic-English bilinguals (Soliman, 2014). These authors had 615 children aged 8-12 complete 12 different tasks assessing four components of working memory. Soliman found that bilingual children outperformed their monolingual counterparts in working memory, but only when the author examined the latent variables underlying working memory tasks (2014). Differences between monolinguals and bilinguals were more pronounced in the complex tasks that maximize cognitive load (Soliman, 2014), supporting previous findings that a bilingual advantage may be most measurable when task demands are high (Sullivan et al., 2014).

Neuropsychological tasks provide measures of accuracy and reaction time but may lack sensitivity to determine if there are differences between monolinguals and bilinguals during the decision-making process. Using electrophysiological tools such as event-related potentials (ERPs) may provide insight into group differences not observed when using behavioral measures alone. ERPs measure the underlying neural processing associated with specific cognitive events. They have excellent temporal resolution and thus may be more sensitive to language differences than performance measures alone. The P2, N2, and P3b ERP components will be examined in the preset study because of their association with working memory.

The P2 is an anterior maximal positive-going component that occurs approximately 150-300 ms post-stimulus presentation. Associated with attentional control in working memory, larger P2 amplitudes reflect both enhanced attentional allocation and working memory processing (Finnigan et al., 2011; Li, Tang, & Chen, 2016). The N2 component is also an anterior maximal component but is a negative-going waveform that occurs between 200 and 350 ms post-stimulus presentation. Reflecting effort during task completion (Pinal & Díaz, 2014), larger N2 amplitudes suggest greater effort required to complete the task. Finally, the P3b is a positive-going component that typically occurs between 250 and 600 ms following stimulus presentation (Polich, 2007). The P3b typically decreases with increasing task difficulty, reflecting a decrease in the availability of resources for task completion (Kok, 2001; Polich, 2007).

Several studies have reported differences in N2 and P3b amplitude between bilinguals and monolinguals when performing executive functioning tasks (Barac et al., 2016; Kousaie & Phillips, 2012b; Moreno et al., 2014; Sullivan et al., 2014). In some of these studies, electrophysiological differences were observed in the absence of behavioral differences (Barac et al., 2016; Grundy et al., 2017; Kousaie & Phillips, 2012b). Taken together, these results provide evidence for differences in brain processing between monolinguals and bilinguals during cognitive tasks, even when a behavioral bilingual advantage may not be present.

We previously reported ERP differences between English monolinguals and English-French bilinguals in the absence of performance differences in both an n-back working memory task (Morrison et al., 2018) and a delayed matching-to-sample task (DMS) (Morrison, Kamal, Le, et al., 2019). Here we compare the same sample of English monolinguals and English-French bilinguals to a group of Arabic-English bilinguals on these tasks. Because English and French are more closely related than English and Arabic, we expected that during the DMS task Arabic-English bilinguals would display larger P2 and P3b and smaller N2 amplitudes than both the English monolinguals and English-French bilinguals. These ERP differences would reflect enhanced attentional allocation, working memory processing, and reduced effort needed for task completion. To our knowledge, this study is the first to examine cognitive processing using ERPs in Arabic-English bilinguals.

2. Methods

For this study, 23 young adult Arabic-English bilinguals (15 females**),** aged 18-30 were recruited through word of mouth and the University of Ottawa. These participants had high self-reported proficiency in both their L1 and L2. They were then compared to younger adult English monolingual and English-French bilinguals whose data has been previously published. Twenty-six English monolingual and 28 English-French bilinguals completed the delayed matching-to-sample task; 32 English monolinguals and 31 English-French bilinguals completed the n-back task[7]. All 23 Arabic-English bilinguals completed both tasks. Demographic information and neuropsychological test scores are provided in Table 1.

<Insert Table 1 about here>

Participants completed health questionnaire by phone to exclude for 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. During the phone screen, participants also completed a self-report language questionnaire for English, French, and Arabic. Participants were required to rate their fluency in listening, reading, speaking, and writing on a scale of 1 (no ability) to 5 (native like ability). Bilinguals had to rate

[7] The English monolingual and English-French bilingual data have been published previously.

all categories at a 4 or 5, with the exception of writing which could be a 3. Monolinguals had to rate their English at 4 or 5 across all categories and could not rate any other language above a 2 (very little ability) in any modality. Potential participants who rated knowledge of another language (other than English, French, or Arabic) above a 2 were also excluded. In addition, bilinguals completed a language questionnaire to assess frequency of use for both their L1 and L2 (scores are provided in Table 2).

This study received ethical approval from both the Bruyère Research Institute and the University of Ottawa ethics board; participants provided informed written consent before starting the study and were compensated $10 an hour.

<Insert Table 2 about here>

3. Procedure:

Participants completed three testing sessions lasting approximately 1.5 hours each. In the first session, participants completed a neuropsychological test battery to assess language proficiency and cognitive functioning. This battery included the Montreal Cognitive Assessment (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 & 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). English-French bilingual participants completed the fluency tasks and BNT in both English and French. Arabic-English participants completed the animal fluency in both English and Arabic. During the second and third sessions, participants completed the delayed matching-to-sample and n-back tasks while EEG, accuracy, and reaction times were recorded.

3.1 Delayed matching-to-sample task

This task included three levels of task difficulty (low load, 1 number; medium load, 3 numbers; high load; 5 numbers). For each condition the task began with a fixation cross on the screen for 1000 ms, followed by the memory array which the participant was asked to memorize, then a blank screen for 500 ms, and a probe stimulus for 1500 ms. Participants were asked to indicate if the probe stimulus matched one of the previous numbers in the memory array. To respond participants pressed either the “A” key to indicate that the stimulus was previously presented or the “L” key to indicate that the stimulus was not previously presented. Because the memory array had three different memory loads, the time of presentation varied between set size. For low load, the memory array was presented for 1200 ms, in medium load the memory array was presented for 3600 ms, and for the high load, the memory array was presented for 6000 ms. There were 120 trials per condition.

3.2 N-back task

The N-back task also had three different memory load conditions (0-back, 1-back, 2-back). In the 0-back participants were asked to press the left mouse key when the number 0 appeared. In the 1-back participants were asked to press the left mouse key when the number matched the number presented immediately before (e.g., an 8 followed by another 8), and in the 2-back participants were asked to press the left mouse key when the number displayed matched the number presented two trials before (e.g., an 8 followed by a 4 then another 8). Each memory load block consisted of 180 trials, lasting approximately 10 minutes each, totaling approximately 30 minutes. All numbers were presented for 1000 ms with an inter-stimulus interval of 1700 ms.

3.2 EEG data recording

EEG recording was kept consistent in both tasks. EEG activity was recorded using 31 active silver-silver electrodes attached to an electrode cap (Brain Products, GmbH, Munich, Germany) and placed according to the international 10-20. The Oz electrode was placed on the infraorbital ridge of the left eye to record vertical eye blinks. 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 EEG 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 then visually inspected for high levels of noise, noisy channels were replaced by interpolating the data of surrounding electrode sites (Perrin et al., 1989). Low levels of noise resulted in interpolation being completed in five participants on temporal and occipital electrode sites not of interest to the study. Vertical eye movements were calculated by subtracting the infraorbital electrode from the FP1 electrode. Horizontal eye movements were computed by subtracting F7-F8. Independent Components Analysis was used to identify and remove eye movements and blink artifacts that were statistically independent of the EEG activity (Makeig, Bell, & Sejnowski, 1996). These vertical and horizontal eye movements were then partialled out from the EEG activity. Lastly, 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.

4. Statistical analysis and Results

4.1 Neuropsychological data

All neuropsychological data are presented in Table 1. Scores were analyzed in a MANOVA with language as a fixed factor and neuropsychological test scores as the dependent variable.

4.2 Behavioral data analysis

Accuracy and reaction time by language are presented in Table 3 (delayed matching-to-sample) and Table 4 (n-back). Trials exceeding ±2.5 standard deviations for the mean were excluded as outliers. The analysis of accuracy and reaction was completed using a mixed ANOVAs with the within-subject factor of Condition (Low, Medium, and High load) and the between-subjects factor of Language (Monolingual, English-French Bilingual, Arabic-English Bilingual).

4.3 ERP analysis

Three components were selected for analysis in both tasks: the P2, N2, and P3b. For all three components, three regions of interest were chosen for analysis. Frontal (F3, Fz, F4), Fronto-central (FC1, FCz, FC2), and Central (C3, Cz, C4) were analyzed together in one ANOVA. The within-subjects factors were ROI (Frontal, Fronto-central, Central) and Condition (Low, Medium, High) and the between-subjects factor was Language (Monolingual, English-French Bilingual, and Arabic-English Bilingual). For the P3b the parietal sites were also analyzed (P3, Pz, P4) in a separate ANOVA. The within-subjects factor was Condition (Low, Medium, High load) and the between-subjects factor was Language (Monolingual, English-French Bilingual, and Arabic-English Bilingual).

4.4 DMS performance results

Performance data is presented in Table 3. Working memory load had a significant effect on performance measures. Accuracy was lower in the high load than the medium ($p<.001$) and low load ($p<.001$; main effect of Task Difficulty, $F(2,146)=22.83$, $p<.001$, $n^2_p=.24$). Reaction time became longer with increasing task difficulty with all levels significantly differing, ($p<.001$; main effect of Task difficulty, $F(2,146)=223.97$, $p<.001$, $n^2_p=.75$) No main effects of interactions involving language was significant in either accuracy or reaction time.

4.5 DMS ERP results

Figure 1 illustrates the ERP deflections elicited by the target stimulus across conditions. The anterior maximum P2 occurred at approximately 190 ms. Following the P2 was the N2, which again was maximal over anterior regions and occurred around 280 ms post-stimulus presentation. The P3b had a widespread scalp distribution which occurred between 290-390 ms post stimulus presentation.

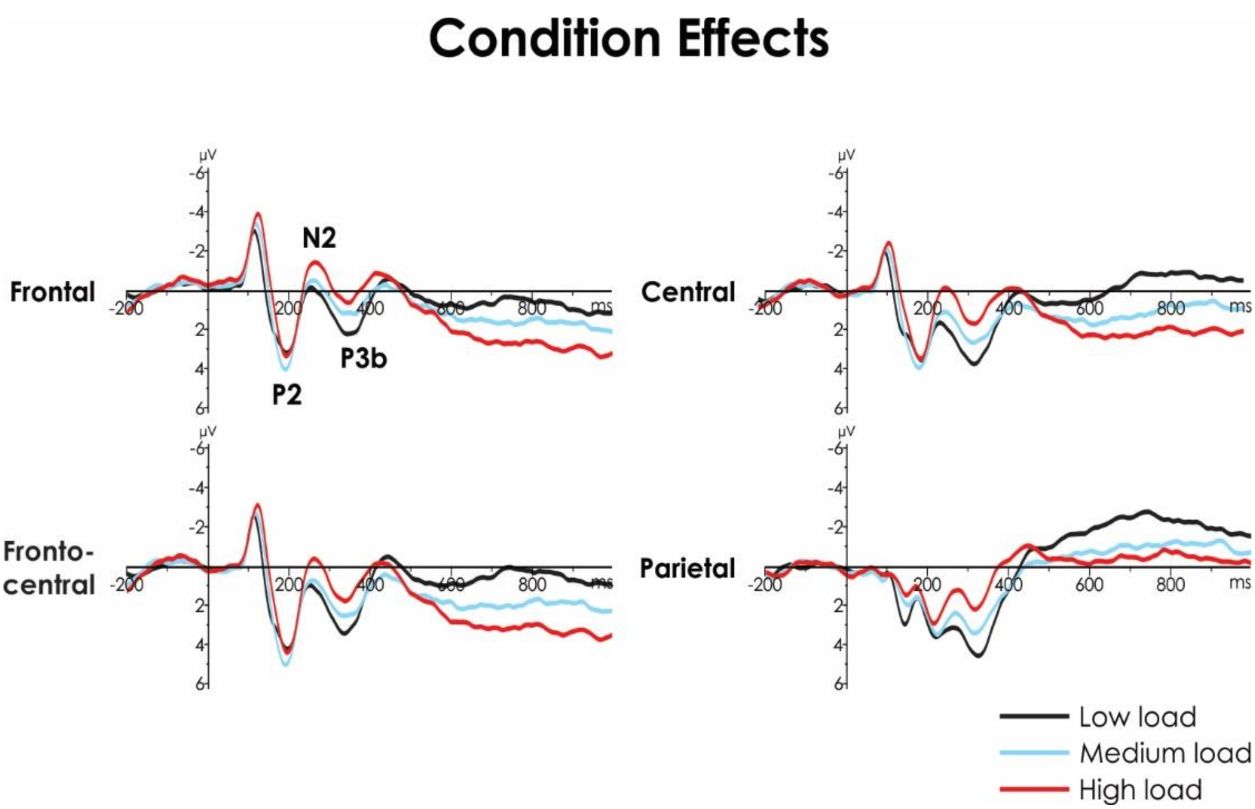

Figure 1. Grand averaged ERP waveforms collapsing across language to show the main effect of task difficulty during the DMS task. Averages at frontal (F3, Fz, F4), fronto-central (FC1, FCz, FC2), central (C3, Cz, C4), and parietal (P3, Pz, P4) regions are shown. Negative is plotted upwards.

4.5.1 P2 (mean amplitude: 170-210)

The anterior P2 analysis revealed that medium load elicited the largest amplitude compared to low (p=.009) and high load (p=.003) which did not differ (main effect of Task Difficulty, $F(2,146)=5.07$, $p=.014$, $n^2_p=.07$). No main effects or interactions involving language were significant.

4.5.2 N2 (mean amplitude: 220-320)

N2 amplitude in anterior regions became larger with increasing memory load, with all conditions significantly differing ($p \leq .018$; main effect of Task Difficulty, $F(2,146)=15.15$, $p<.001$, n^2_p =.17). This analysis also revealed that monolinguals had larger amplitudes than both English-French bilinguals (p=.032) and Arabic-English bilinguals (p=.018), irrespective of task difficulty (main effect of Language, $F(2,73)=3.60$, $p=.032$, $n^2_p=.09$). English-French bilinguals did not differ from Arabic-English bilinguals (p=.69). Interactions involving language were not significant.

4.5.3 P3b (mean amplitude: 250-450)

The anterior P3b amplitude was affected by memory load as amplitude was smallest in the high load compared to both medium and low load ($p<.001$), (main effect of Task Difficulty, $F(2,146)=11.59$, $p<.001$, $n^2_p=.14$). With respect to language, a trending effect showed that English-French bilinguals had the largest P3b amplitude, but was only significantly larger than English monolinguals (p=.023; main effect of Language $F(2,73)=3.60$, $p=.073$, $n^2_p=.07$). Arabic-English bilinguals' P3b amplitude did not differ from either monolinguals or English-French bilinguals. Interactions involving language were not significant.

The parietal ROI analysis also showed that amplitude was influenced by working memory load. P3b amplitude became smaller with increasing memory load, with all conditions significantly differing ($p \leq .008$; main effect of Task Difficulty, $F(2,146)=32.74$, $p<.001$, n^2_p =.31). Main effects and interactions involving language were not significant.

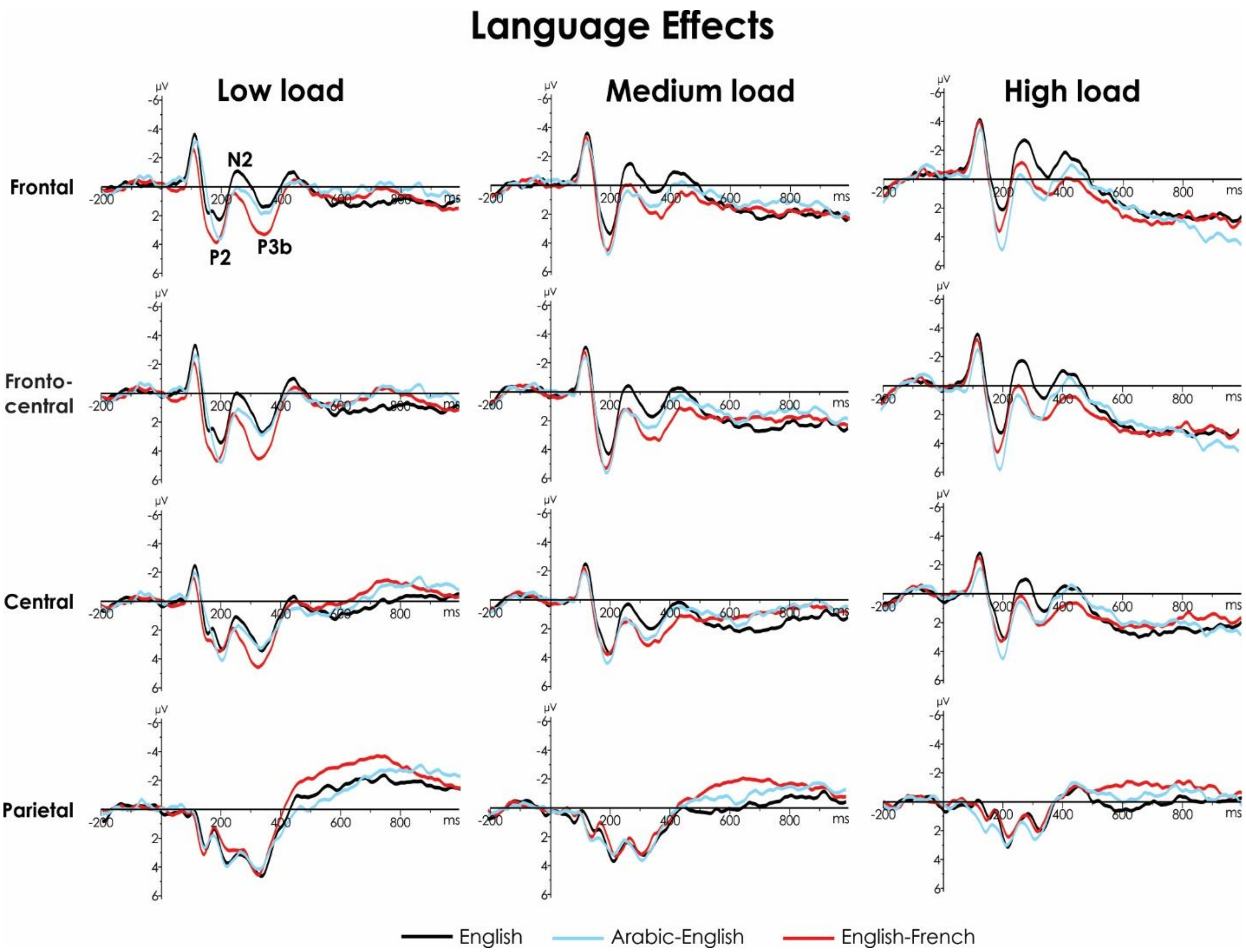

Figure 2. Grand averaged ERP waveforms during the DMS task for each group at frontal (F3, Fz, F4), fronto-central (FC1, FCz, FC2), central (C3, Cz, C4), and parietal (P3, Pz, P4). Negative is plotted upwards. English-French and Arabic-English bilinguals had smaller N2b amplitudes than English monolinguals. English-French bilinguals displayed larger P3b amplitudes than English Monolinguals.

4.6 N-back performance results

Performance data is presented in Table 4. Similar to the delayed matching-to-sample results, accuracy and reaction time were both influenced by working memory load. Correct responses to the target were categorized at target accuracy whereas overall accuracy included both responses and null responses. Target accuracy decreased with increasing memory load, with all conditions significantly differing (main effect of Task Difficulty, $F(2,162)=176.07$, $p<.001$, $n^2_p=.69$). Overall accuracy also decreased with increasing task difficulty, with all conditions significantly differing (main effect of Task Difficulty, $F(2,162)=441.07$, $p<.001$, $n^2_p=.85$). There were no main effects or interactions involving language on task difficulty. Reaction time became longer with increasing task (main effect of Task Difficulty, $F(2,162)=104.86$, $p<.001$, $n^2_p=.56$) with all conditions significantly differing ($p<.001$). A main effect of Language, ($F(2,81)=3.16$, $p=.048$, $n^2_p=.07$), revealed a trend for Arabic bilinguals to respond more slowly than French bilinguals, irrespective of condition ($p=.056$).

4.7 N-back ERP results

Figure 3 illustrates ERP waveforms by condition collapsed across language. The P2 was maximal over frontal regions and occurred around 200 ms. The following component, the N2, occurred around 275 ms. The P3b occurred between 275-475 ms post-stimulus presentation.

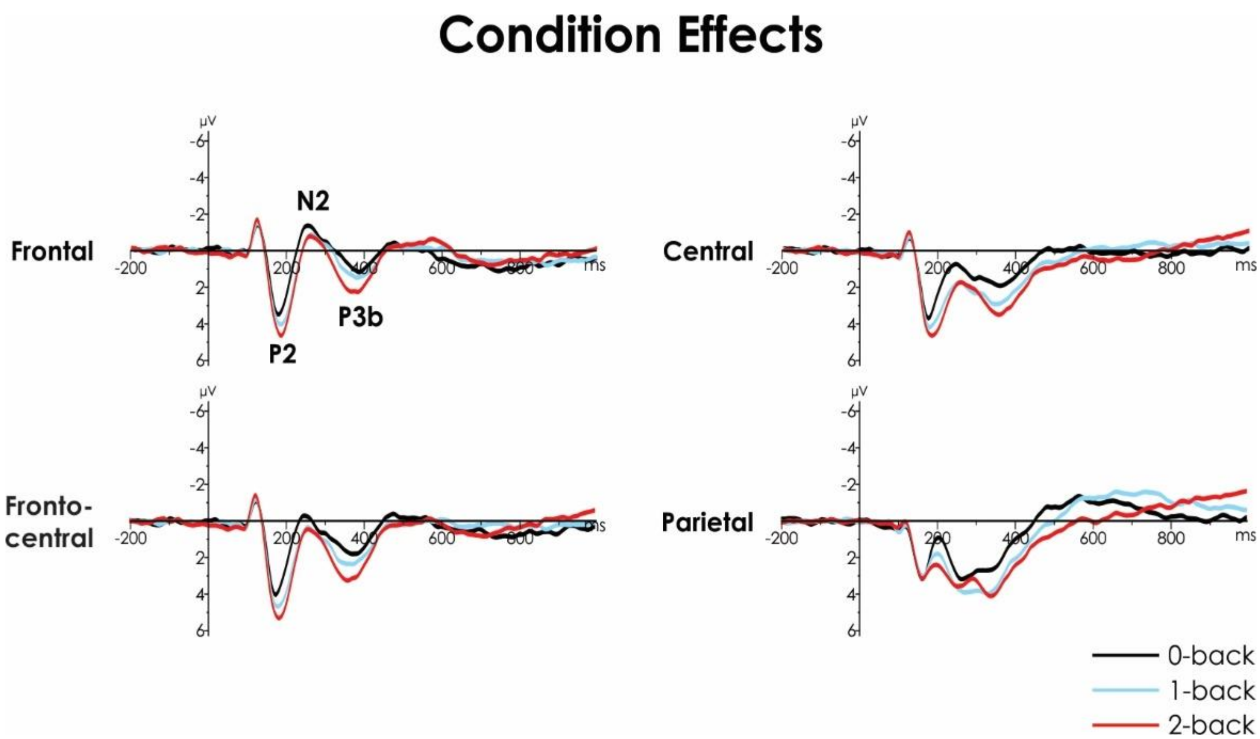

Figure 3. Grand averaged ERP waveforms collapsing across language to show the main effect of task difficulty in the n-back task. Averages at frontal (F3, Fz, F4), fronto-central (FC1, FCz, FC2), central (C3, Cz, C4), and parietal (P3, Pz, P4) regions are shown. Negative is plotted upwards.

4.7.1 P2 (mean amplitude:125-225)

P2 amplitude became larger in with increasing task difficulty, with all conditions significantly differing ($p \leq .009$; main effect of Task Difficulty, $F(2,164)=24.28$, $p<.001$, $n^2_p=.23$). No main effects or interactions involving language were significant.

4.7.2 N2 (mean amplitude: 215-340)

The N2 analysis in anterior regions showed that with increasing task difficulty the N2 amplitude became smaller, with all conditions significantly differing ($p \leq .014$; main effect of Task Difficulty, $F(2,164)=21.61$, $p<.001$, $n^2_p=.21$). Interactions and main effects involving language were not significant.

4.7.3 P3b (mean amplitude: 275-475)

The anterior region analysis revealed that with increasing memory load P3b amplitude increased, with all conditions significantly differing ($p \leq .007$; main effect of Task Difficulty, $F(2,164)=20.38$, $p<.001$, $n^2_p=.20$). English-French bilinguals exhibited larger amplitude than both monolinguals ($p=.009$) and Arabic-English bilinguals ($p=.005$), (main effect of Language, $F(2,82)=5.34$, $p=.007$, $n^2_p=.12$). The language by task difficulty interaction was not significant.

The parietal ROI analysis showed only one significant effect: P3b amplitude became larger from 0-back to 1-back ($p<.001$) and 2-back ($p<.001$) which did not differ from each other, (main effect of Task Difficulty, $F(2,164)=41.30$, $p<.001$, $n^2_p=.33$). There was a trending effect for English-French bilinguals to have larger P3b amplitudes than Arabic-English bilinguals ($p=.025$; main effect of Language, $F(2,82)=2.62$, $p=.079$, $n^2_p=.12$). The language by task difficulty interaction was not significant. A summary of ERP results is presented in Table 5.

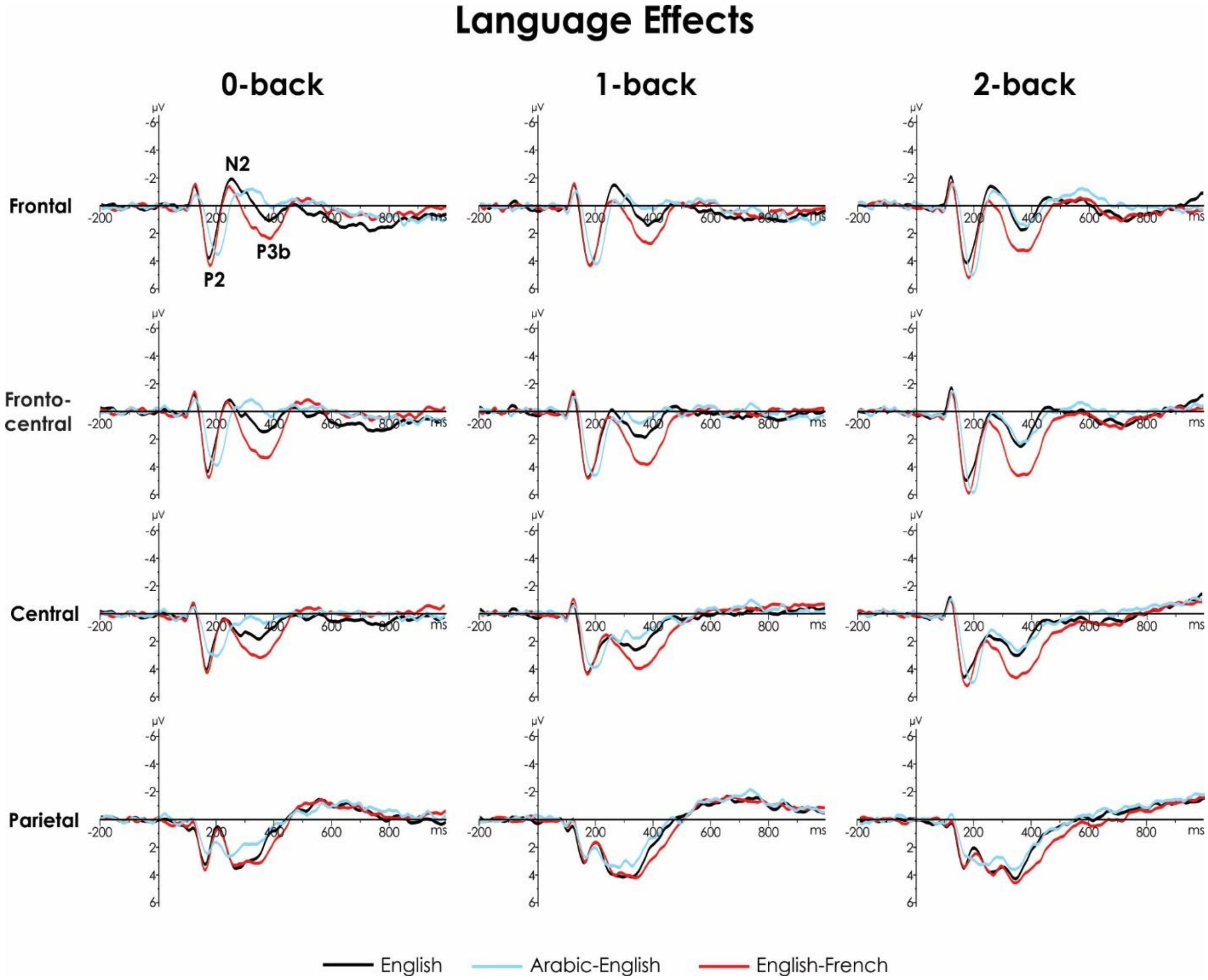

Figure 4. Grand averaged ERP waveforms during the n-back task for each group at frontal (F3, Fz, F4), fronto-central (FC1, FCz, FC2), central (C3, Cz, C4), and parietal (P3, Pz, P4) regions. Negative is plotted upwards. English-French bilinguals displayed larger P3b amplitudes than both English monolinguals and Arabic-English bilinguals.

<Insert Table 5 about here>

5.0 Discussion

In two previous studies (Morrison, Kamal, Le, et al., 2019; Morrison et al., 2018), we reported ERP differences in monolingual and bilingual young adults in the absence of a bilingual working memory advantage. In those studies, we compared English-French bilinguals to English monolinguals. English and French are, however, both Indo-European languages and share many similarities. The goal of this study was to examine if a bilingual advantage in working memory is more pronounced in a language more linguistically distant from English than French. Arabic is more distant from English, and as such English and Arabic share fewer similarities than English and French. Thus, more resources may be required to manage and switch between English and Arabic than English and French. Most studies that examine the effects of bilingualism between two languages have been carried out almost exclusively using Indo-European languages. In these studies, researchers typically base conclusions on the results from behavioral measures. The present study examined behavioral measures and ERPs elicited from two working memory tasks. We compared a sample of Arabic-English bilinguals to English monolinguals and English-French bilinguals. Although no behavioral differences were observed in the two working memory tasks, some neuropsychological task scores and ERPs were notably different.

5.1 Neuropsychological data

Neuropsychological data differed among all three groups. Arabic-English bilinguals achieved lower scores on several tasks compared to both monolinguals and English-French bilinguals. Lower scores in Arabic bilinguals may have been a confound of the fact that neuropsychological tasks were completed in English. Lower scores on some fluency measures for the Arabic-English bilinguals coincides with their lower self-reported English proficiency. Arabic-English bilinguals also had lower scores on the Stroop2 and MoCA (compared to monolinguals and English-French bilinguals) and on the WCST and Digit Symbol-Oral (compared to English-French bilinguals). The MoCA is a measure of general cognitive functioning and is often used as a marker of cognitive impairment and thus should not differ between young adults. All three groups comprised relatively similar young adult university students. Thus, we expected that their MoCA scores would not differ. Lower scores in the Arabic-English bilingual sample may be related to cultural differences between the groups (for a review of cross-cultural applicability of the MoCA see O'Driscoll & Shaikh, 2017). O'Driscoll & Shaikh (2017) note that lifestyle factors (e.g., employment, diet, and activities), education, and cultural factors (e.g., shared knowledge, beliefs, values, and attitudes) vary between Eastern and Western countries. These differences affect the validity of cognitive tests such as the MoCA in non-western cultures. Future research should examine how scores on neuropsychological tasks may vary between cultures and how these differences may interact with and affect group differences.

Monolinguals scored lower on the letter-number sequencing than English-French bilinguals. This result is consistent with previous research finding lower working memory capacity in monolinguals compared to bilinguals (Kudo & Swanson, 2014; Morales et al., 2013). Arabic-English bilinguals did not differ from English monolinguals or English-French bilinguals on the letter-number sequencing task. Various results in the neuropsychological data suggest that differences between monolinguals and bilinguals may be observed on specific cognitive tasks or may only occur between specific languages.

5.2 Behavioral data

Participants also completed two working memory tasks while EEG was recorded, the delayed matching-to-sample and n-back. In the delayed matching-to-sample, participants were presented with a memory array (1, 3, or 5 numbers) followed by a single number. The participants had to memorize the memory array and indicate if the single number presented was in the previous memory array. In the n-back, participants were asked to only respond when the number presented matched the number from n-times before (0-, 1-, 2-back). As expected, task load influenced behavioral measures in both tasks. In the delayed matching-to-sample task, accuracy was higher in the low load than the medium and high load conditions. Accuracy in the n-back was also higher with lower memory load. Memory load also influenced reaction time. In both tasks, reaction time increased with increasing task load. Importantly, there were no significant group differences or interactions involving group for accuracy or reaction time on either of the tasks. These results suggest that there is no bilingual advantage in working memory as measured by the delayed matching-to-sample and n-back task.

5.2 ERP data

Working memory load influenced both the N2 and P3b amplitude. In the delayed matching-to-sample task, N2 amplitude increased and P3b amplitude decreased with increasing task difficulty. Several studies using the delayed matching-to-sample task have observed similar findings (e.g., Morgan, Klein, Boehm, Shapiro, & Linden, 2008; Speer & Soldan, 2015). Results in the n-back were opposite to those found in the delayed matching-to-sample. Consistent with past research, N2 amplitude decreased (Daffner et al., 2011) and P3b amplitude increased (Deiber et al., 2015) with increasing task difficulty. Task-dependent ERP differences has been interpreted as different processing demands required for each task. Decreased P3b amplitude with increasing task load in the delayed matching-to-sample task might be because of increased cognitive demands to process more stimuli (Polich, 2007). Increased P3b amplitudes with increasing task difficulty in the n-back task could be because of the dual-task nature of the paradigm (i.e., the maintenance, encoding, and processing of stimuli occurs simultaneously) (Polich, 2007; Watter, Geffen, & Geffen, 2001).

The N2 analysis revealed inconsistent results between tasks. Monolinguals displayed larger amplitude N2s than both the English-French and Arabic-English bilinguals during the delayed matching-to-sample task. However, in the n-back, the N2 amplitude did not differ between groups. Researchers have suggested that the N2 may reflect cognitive effort (Folstein & Van Petten, 2008; Pinal & Díaz, 2014). A large N2 may thus reflect the need for additional effort for task completion. The smaller N2 in bilinguals during the delayed matching-to-sample task is consistent with the need for bilinguals to exert less effort to successfully complete the task than monolinguals. Monolinguals may thus require more effort to maintain similar performance to that of the two bilingual groups during only the delayed matching-to-sample task.

Most studies examining the N2 have noted larger amplitudes in bilinguals compared to monolinguals (e.g., Kousaie & Phillips, 2012; López Zunini, Morrison, Kousaie, & Taler, 2019; Moreno, Wodniecka, Tays, Alain, & Bialystok, 2014). The larger N2 amplitudes in bilinguals may reflect enhanced executive control and conflict resolution in bilinguals compared to monolinguals (Moreno et al., 2014). In the current study, we employed working memory tasks, therefore our N2 is interpreted as reflecting cognitive effort as opposed to conflict monitoring. Differences between task demands could explain why we observed a smaller N2 in bilinguals compared to monolinguals.

Both the delayed matching-to-sample and n-back tasks elicited P3b language group differences. English-French bilinguals' anterior P3b amplitude was larger than the monolinguals during the delayed matching-to-sample task. The difference between the two bilingual groups was not significant. In the n-back task, the anterior P3b amplitude for the English-French bilinguals was larger than that of both the monolinguals and the Arabic-English bilinguals. The P3b has been associated with several cognitive processes including attention, resource allocation, and memory (for a review see Polich, 2007). Thus, a larger P3b in English-French bilinguals may be understood as this group maintaining attention on the task whereas the monolinguals and Arabic-English bilinguals were not. Some researchers have also suggested that a larger P3b might reflect the ease of decision making and the availability of cognitive resources for successful task completion (e.g., Kok, 2001). Using this theory, a larger P3b in English-French bilinguals could, therefore, result from the availability of additional cognitive resources, allowing a decision to be made with greater ease. When taking into consideration the behavioral data these interpretations are difficult to justify. If English-French bilinguals were more attentive during the task or had additional cognitive resources they should have also achieved better behavioral outcomes. P3b amplitude differences between our English-French bilinguals and the Arabic-English bilinguals and monolinguals could thus be interpreted as differences in the processing strategies used for task completion rather than a bilingual advantage.

Previous studies examining ERPs in monolinguals and bilinguals reported P3b group differences. Several studies found that bilinguals exhibit larger P3b amplitudes compared to monolinguals (Barac et al., 2016; Moreno et al., 2014; Sullivan et al., 2014). The authors interpreted the larger P3b in bilinguals as heightened executive control processes compared to monolinguals. The P3b has also been observed to be smaller in bilinguals compared to monolinguals (Kousaie & Phillips, 2012b; López Zunini et al., 2019). During a Simon task, the smaller amplitude P3b may be interpreted as task completion being more effortful for bilinguals (Kousaie & Phillips, 2012b). Another interpretation of the smaller P3b in bilinguals, suggests bilinguals may use different processing strategies than monolinguals (López Zunini et al., 2019).

N2 and P3b language group differences were not consistent between the tasks. One possible explanation of this difference is because of the cognitive processes thought to be involved in the completion of the tasks. As mentioned, several researchers have suggested that the n-back is a dual-task paradigm because it may activate many processes simultaneously (e.g., encoding, storage, updating, matching) (Watter et al., 2001). On the other hand, completing the delayed matching-to-sample may use the phonological loop and articulatory rehearsal components of working memory (Baddeley, 2000; Germano & Kinsella, 2005). Larger N2 amplitudes in monolinguals compared to both bilingual groups in only the delayed matching-to-sample task may thus reflect the need for more effort when activating the phonological loop. It is not surprising that monolinguals may require more effort when activating the phonological loop given the relationship between the phonological loop and language acquisition (Atkins & Baddeley, 1998). Future research should replicate this study with a more difficult delayed matching-to-sample task to better understand the interaction between language group, task difficulty, and the components of working memory.

5.3 Limitations

There are a few limitations of the current study to mention. The Arabic-English bilinguals reported lower English proficiency than the English-French bilinguals. There were also significant language usage differences between Arabic-English and English-French bilinguals. Although Arabic-English bilinguals used Arabic more at home for communication, they used Arabic less at school than the English-French bilinguals used French. Arabic-English bilinguals listened and spoke in Arabic at home 30% more than English-French bilinguals listened and spoke in French at home. At school/work, English-French bilinguals used French almost 30% more across all modalities (listening, reading, speaking, and writing). The context in which these bilinguals use their language may influence their level of proficiency in both languages. Future research should replicate this study with a larger sample size that has similar proficiencies in both their languages.

6.0 Conclusions

The present study examined whether a bilingual advantage is more pronounced in Arabic-English bilinguals during two working memory tasks. We found that monolinguals exhibited smaller N2 amplitudes compared to both bilingual groups in the delayed matching-to-sample task. Smaller N2 amplitudes in monolinguals may suggest increased effort needed when completing a task which requires the phonological loop component of working memory. English-French bilinguals exhibited larger P3b amplitudes than monolinguals in both tasks and larger P3b amplitudes than Arabic-English bilinguals in the n-back task. Larger P3b amplitudes in the English-French bilinguals may be interpreted as these bilinguals using different cognitive strategies and processing for task completion. Taken together, these findings suggest that Arabic-English bilinguals do not display enhanced working memory processing compared to English-French bilinguals or English monolinguals despite sharing fewer similarities with English than French.

References

Abutalebi, J., Della Rosa, P. A., Green, D. W., Hernandez, M., Scifo, P., Keim, R., ... & Costa, A. (2012). Bilingualism tunes the anterior cingulate cortex for conflict monitoring. *Cerebral Cortex*, *22*(9), 2076-2086.

Alloway, T. P., & Alloway, R. G. (2010). Investigating the predictive roles of working memory and IQ in academic attainment. *Journal of Experimental Child Psychology*, 106(1), 20-29. https://doi.org/10.1016/j.jecp.2009.11.003

Atkins, P. W., & Baddeley, A. D. (1998). Working memory and distributed vocabulary learning. *Applied Psycholinguistics*, *19*(4), 537-552. https://doi.org/doi:10.1017/S0142716400010353

Baddeley, A. (2000). The episodic buffer: a new component of working memory? *Trends in Cognitive Sciences*, *4*(11), 417-423.

Baddeley, A. (2003). Working memory: looking back and looking forward. *Nature Reviews Neuroscience*, *4*(10), 829-839.

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

Badzakova-Trajkov, G. (2008). *A behavioural and functional imaging investigation of Stroop task performance in late proficient bilinguals* (Doctoral dissertation, ResearchSpace@ Auckland).

Barac, R., Moreno, S., & Bialystok, E. (2016). Behavioral and electrophysiological differences in executive control between monolingual and bilingual children. *Child Development*, *87*(4), 1277-1290. DOI: 10.1111/cdev.12538

Bialystok, E., Craik, F. I., Grady, C., Chau, W., Ishii, R., Gunji, A., & Pantev, C. (2005). Effect of bilingualism on cognitive control in the Simon task: Evidence from MEG. *NeuroImage*, 24(1), 40-49. doi: 10.1016/j.neuroimage.2004.09.044

Bialystok, E., Craik, F., & Luk, G. (2008). Cognitive control and lexical access in younger and older bilinguals. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *34*(4), 859. https://doi.org/10.1037/0278-7393.34.4.859

Blom, E., Küntay, A. C., Messer, M., Verhagen, J., & Leseman, P. (2014). The benefits of being bilingual: Working memory in bilingual Turkish–Dutch children. *Journal of Experimental Child Psychology*, *128*, 105-119. https://doi.org/10.1016/j.jecp.2014.06.007

Borkowski, J. G., Benton, A. L., & Spreen, O. (1967). Word fluency and brain Damage. *Neuropsychologia*, *5*(2), 135-140

Brinton, L. J., & Brinton, D. (2010). *The linguistic structure of modern English*. John Benjamins Publishing.

Burgaleta, M., Sanjuán, A., Ventura-Campos, N., Sebastian-Galles, N., & Ávila, C. (2016). Bilingualism at the core of the brain. Structural differences between bilinguals and monolinguals revealed by subcortical shape analysis. *NeuroImage*, 125, 437-445.

Carlson, S. M., & Meltzoff, A. N. (2008). Bilingual experience and executive functioning in young children. *Developmental Science*, *11*(2), 282-298. https://doi.org/10.1111/j.1467-7687.2008.00675.x.Bilingual

Daffner, K. R., Chong, H., Sun, X., Tarbi, E. C., Riis, J. L., McGinnis, S. M., & Holcomb, P. J. (2011). Mechanisms underlying age-and performance-related differences in working memory. *Journal of Cognitive Neuroscience*, *23*(6), 1298-1314. https://doi.org/10.1162/jocn.2010.21540.Mechanisms

De Bruin, A., Treccani, B., & Della Sala, S. (2015). Cognitive advantage in bilingualism: An example of publication bias? *Psychological Science*, *26*(1), 99-107. https://doi.org/10.1177/0956797614557866

Deiber, M. P., Meziane, H. B., Hasler, R., Rodriguez, C., Toma, S., Ackermann, M., ... & Giannakopoulos, P. (2015). Attention and working memory-related EEG markers of subtle cognitive deterioration in healthy elderly individuals. *Journal of Alzheimer's Disease*, *47*(2), 335-349.

Duñabeitia, J. A., Hernández, J. A., Antón, E., Macizo, P., Estévez, A., Fuentes, L. J., & Carreiras, M. (2014). The inhibitory advantage in bilingual children revisited. *Experimental Psychology*. https://doi.org/10.1027/1618-3169/a000243

Eberhard, David M., Gary F. Simons, and Charles D. Fennig (eds.). 2020. Ethnologue: Languages of the World. Twenty-third edition. Dallas, Texas: SIL International. Online version: http://www.ethnologue.com.

Fejzo, A. (2016). The contribution of morphological awareness to the spelling of morphemes and morphologically complex words in French. *Reading and Writing*, 29(2), 207-228. DOI 10.1007/s11145-015-9586-8

Finnigan, S., O'Connell, R. G., Cummins, T. D., Broughton, M., & Robertson, I. H. (2011). ERP measures indicate both attention and working memory encoding decrements in aging. *Psychophysiology*, *48*(5), 601-611. https://doi.org/10.1111/j.1469-8986.2010.01128.x

Folstein, J. R., & Van Petten, C. (2008). Influence of cognitive control and mismatch on the N2 component of the ERP: a review. *Psychophysiology*, *45*(1), 152-170. https://doi.org/10.1111/j.1469-8986.2007.00602.x

García, MI, & Borges de Souza, AM (2014). Lexical similarity level between English and Portuguese. *ELIA*, *14*, *145-163*. https://doi.org/10.12795/elia.2014.i14.06

Gathercole, V. C. M., Thomas, E. M., Kennedy, I., Prys, C., Young, N., Viñas-Guasch, N., ... & Jones, L. (2014). Does language dominance affect cognitive performance in bilinguals? Lifespan evidence from preschoolers through older adults on card sorting, Simon, and metalinguistic tasks. *Frontiers in Psychology*, *5*, 11. https://doi.org/10.3389/fpsyg.2014.00011

Germano, C., & Kinsella, G. J. (2005). Working memory and learning in early Alzheimer's disease. *Neuropsychology Review*, *15*(1), 1-10. https://doi.org/10.1007/s11065-005-3583-7

Goldman, M. C., Negen, J., & Sarnecka, B. W. (2014). Are bilingual children better at ignoring perceptually misleading information? A novel test. *Developmental Science*, *17*(6), 956-964. https://doi.org/10.1111/desc.12175

Grant, D. A., & Berg, E. (1948). A behavioral analysis of degree of reinforcement and ease of shifting to new responses in a Weigl-type card-sorting problem. *Journal of Experimental Psychology*, *38*(4), 404.

Grundy, J. G., Anderson, J. A., & Bialystok, E. (2017). Bilinguals have more complex EEG brain signals in occipital regions than monolinguals. *NeuroImage*, *159*, 280-288. https://doi.org/10.1016/j.neuroimage.2017.07.063

Grundy, J. G., & Timmer, K. (2017). Bilingualism and working memory capacity: A comprehensive meta-analysis. *Second Language Research*, *33*(3), 325-340. https://doi.org/10.1177/0267658316678286

Kaplan, E., Goodglass, H., & Weintraub, S. (1983). The Boston Naming Test. Lea & Febiger. *Philadelphia, PA*.

Kok, A. (2001). On the utility of P3 amplitude as a measure of processing capacity. *Psychophysiology*, *38*(3), 557-577. https://doi.org/10.1016/S0167-8760(98)90168-4

Kovelman, I., Baker, S. A., & Petitto, L. A. (2008). Age of first bilingual language exposure as a new window into bilingual reading development. *Bilingualism: Language and Cognition*, *11*(2), 203-223. https://doi.org/doi:10.1017/S1366728908003386

Kousaie, S., & Phillips, N. A. (2012). Conflict monitoring and resolution: Are two languages better than one? Evidence from reaction time and event-related brain potentials. *Brain Research*, *1446*, 71-90. https://doi.org/10.1016/j.brainres.2012.01.052

Kousaie, S., Sheppard, C., Lemieux, M., Monetta, L., & Taler, V. (2014). Executive function and bilingualism in young and older adults. *Frontiers in Behavioral Neuroscience*, 8, 250.

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

Kousaie, S., Sheppard, C., Lemieux, M., Monetta, L., & Taler, V. (2014). Executive function and bilingualism in young and older adults. *Frontiers in Behavioral Neuroscience*, *8*, 250. https://doi.org/10.3389/fnbeh.2014.00250

Kudo, M., & Swanson, H. L. (2014). Are there advantages for additive bilinguals in working memory tasks? *Learning and Individual Differences*, *35*, 96-102. https://doi.org/10.1016/j.lindif.2014.07.019

Lee Salvatierra, J., & Rosselli, M. (2011). The effect of bilingualism and age on inhibitory control. *International Journal of Bilingualism*, 15(1), 26-37.

Li, B. Y., Tang, H. D., & Chen, S. D. (2016). Retrieval deficiency in brain activity of working memory in amnesic mild cognitive impairment patients: a brain event-related potentials study. *Frontiers in Aging Neuroscience*, *8*, 54. https://doi.org/10.3389/fnagi.2016.00054

Linck, J. A., Osthus, P., Koeth, J. T., & Bunting, M. F. (2014). Working memory and second language comprehension and production: A meta-analysis. *Psychonomic Bulletin & Review*, *21*(4), 861-883. https://doi.org/10.3758/s13423-013-0565-2

López Zunini, R. A., Morrison, C., Kousaie, S., & Taler, V. (2019). Task switching and bilingualism in young and older adults: A behavioral and electrophysiological investigation. *Neuropsychologia, 133*. https://doi.org/10.1016/j.neuropsychologia.2019.107186

Lukasik, K. M., Lehtonen, M., Soveri, A., Waris, O., Jylkkä, J., & Laine, M. (2018). Bilingualism and working memory performance: Evidence from a large-scale online study. *PloS One*, *13*(11). DOI: https://dx.doi.org/10.1371%2Fjournal.pone.0205916

Makeig, S., Bell, A. J., Jung, T. P., & Sejnowski, T. J. (1996). Independent component analysis of electroencephalographic data. *In Advances in Neural Information Processing Systems* (pp. 145-151).

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

Moreno, S., Wodniecka, Z., Tays, W., Alain, C., & Bialystok, E. (2014). Inhibitory control in bilinguals and musicians: Event related potential (ERP) evidence for experience-specific effects. *PLoS ONE*, *9*(4), 1–8. https://doi.org/10.1371/journal.pone.0094169

Morgan, H. M., Klein, C., Boehm, S. G., Shapiro, K. L., & Linden, D. E. (2008). Working memory load for faces modulates P300, N170, and N250r. *Journal of Cognitive Neuroscience*, *20*(6), 989-1002. https://doi.org/10.1162/jocn.2008.20072

Morrison, C., Kamal, F., & Taler, V. (2018). The influence of bilingualism on working memory event-related potentials. *Bilingualism: Language and Cognition*, *22*(1), 191-199. https://doi.org/10.1017/S1366728918000391

Morrison, C., Kamal, F., Le, K., & Taler, V. (2019). Monolinguals and bilinguals respond differently to a delayed matching-to-sample task: an ERP study. *Bilingualism: Language and Cognition*, 1-11. https://doi.org/10.1017/S1366728919000816

Nasreddine, Z. S., Phillips, N. A., Bédirian, V., Charbonneau, S., Whitehead, V., Collin, I., ... & Chertkow, H. (2005). The Montreal Cognitive Assessment, MoCA: a brief screening tool for mild cognitive impairment. *Journal of the American Geriatrics Society, 53*(4), 695-699. https://doi.org/10.1111/j.1532-5415.2005.53221.x

Nichols, E. S., Wild, C. J., Stojanoski, B., Battista, M. E., & Owen, A. M. (2020). Bilingualism Affords No General Cognitive Advantages: A Population Study of Executive Function in

11,000 People. *Psychological Science*, 0956797620903113. https://doi.org/10.1177/0956797620903113

O'Driscoll, C., & Shaikh, M. (2017). Cross-cultural applicability of the Montreal Cognitive Assessment (MoCA): a systematic review. *Journal of Alzheimer's Disease*, *58*(3), 789-801. https://doi.org/10.3233/JAD-161042

Paap, K. R., & Greenberg, Z. I. (2013). There is no coherent evidence for a bilingual advantage in executive processing. *Cognitive Psychology*, *66*(2), 232-258. https://doi.org/10.1016/j.cogpsych.2012.12.002

Perrin, F., Pernier, J., Bertrand, O., & Echallier, J. F. (1989). Spherical splines for scalp potential and current density mapping. *Electroencephalography and Clinical Neurophysiology*, *72*(2), 184-187.

Pinal, D., Zurrón, M., & Díaz, F. (2014). Effects of load and maintenance duration on the time course of information encoding and retrieval in working memory: from perceptual analysis to post-categorization processes. *Frontiers in Human Neuroscience*, *8*, 165. https://doi.org/10.3389/fnhum.2014.00165

Polich, J. (2007). Updating P300: an integrative theory of P3a and P3b. *Clinical Neurophysiology*, *118*(10), 2128-2148. https://doi.org/10.1016/j.clinph.2007.04.019

Prior, A., & Gollan, T. H. (2011). Good language-switchers are good task-switchers: Evidence from Spanish–English and Mandarin–English bilinguals. *Journal of the International Neuropsychological Society*, *17*(4), 682-691. https://doi.org/10.1017/S1355617711000580

Ratiu, I., & Azuma, T. (2015). Working memory capacity : Is there a bilingual advantage ? Journal of Cognitive Psychology, 27(1), 1–11. https://doi.org/10.1080/20445911.2014.976226

Rowe, Bruce M.; Levine, Diane P. (2015). *A Concise Introduction to Linguistics*. Routledge. pp. 340–341. ISBN 1317349288.

Ryding, K. C. (2014). Arabic: A linguistic introduction. Cambridge University Press.

Soliman, Abdrabo Moghazy. "Bilingual advantages of working memory revisited: A latent variable examination." Learning and Individual Differences 32 (2014): 168-177. https://doi.org/10.1016/j.lindif.2014.02.005

Sörman, D. E., Hansson, P., & Ljungberg, J. K. (2019). Different features of bilingualism in relation to executive functioning. *Frontiers in Psychology*, 10. https://dx.doi.org/10.3389%2Ffpsyg.2019.00269

Speer, M. E., & Soldan, A. (2015). Cognitive reserve modulates ERPs associated with verbal working memory in healthy younger and older adults. *Neurobiology of Aging*, *36*(3), 1424-1434. https://doi.org/doi:10.1016/j.neurobiolaging.2014.12.025.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, *18*(6), 643.

Sullivan, M. D., Janus, M., Moreno, S., Astheimer, L., & Bialystok, E. (2014). Early stage second-language learning improves executive control: Evidence from ERP. *Brain and Language*, *139*, 84–98. https://doi.org/10.1016/j.bandl.2014.10.004

Swanson, H. L., & Beebe-Frankenberger, M. (2004). The relationship between working memory and mathematical problem solving in children at risk and not at risk for serious math difficulties. *Journal of Educational Psychology*, *96*(3), 471. https://doi.org/10.1037/0022-0663.96.3.471

Watter, S., Geffen, G. M., & Geffen, L. B. (2001). The n-back as a dual-task: P300 morphology under divided attention. *Psychophysiology*, *38*(6), 998-1003. https://doi.org/10.1111/1469-8986.3860998

Wechsler, D. (1997). Wechsler Memory Scale (WMS-III). San Antonion: TX:Psychological Corportation.

Wierzbicki, S. (2013). *An investigation into the relationship between bilingualism and attentional networks with a focus on linguistic distance and language proficiency* (Doctoral dissertation).

Wu, Y. J., & Thierry, G. (2013). Fast modulation of executive function by language context in bilinguals. *Journal of Neuroscience*, 33(33), 13533-13537. https://doi.org/10.1523/JNEUROSCI.4760-12.2013

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

	English Monolingual	English-French Bilingual	Arabic-English Bilingual	Probability	Partial eta squared (n^2_p)
N (females)	36 (16 females)	36 (20 females)	23 (19 females)	---	
Age	19.50 (2.06)	20.47 (2.12)	18.96 (2.18)	.02	.08
Education	14.39 (1.83)	15.22 (1.71)	13.48 (1.70)	.001	.13
MoCA	28.25 (1.44)	28.17 (1.73)	26.95 (1.58)	**.006***	**.11**
Digit Span Forward	10.64 (2.19)	11.08 (2.64)	10.57 (1.90)	.624	.01
Digit Span Backward	7.06 (1.79)	7.39 (2.52)	7.87 (2.71)	.41	.02
Letter # Sequencing	11.08 (2.11)	12.53 (2.98)	11.91 (2.47)	**.061**	**.06**
WCST	4.28 (1.03)	4.64 (0.83)	4.04 (0.88)	**.048***	**.06**
Stroop1	111.14 (13.24)	109.06 (17.46)	104.39(11.99)	.23	.03
Stroop2	79.86 (10.76)	77.58 (11.51)	70.65 (9.55)	**.007***	**.10**
Stroop3	51.33 (11.10)	53.94 (11.16)	46.17 (8.00)	.024	.08
Stroop1 – Stroop3	59.81 (10.14)	55.11 (16.38)	58.22 (11.77)	.32	.03
Stroop2 – Stroop3	28.52 (8.72)	23.64 (8.93)	24.48 (7.37)	**.042***	**.07**
Digit Symbol-Written	63.50 (11.80)	64.00 (10.51)	58.96 (10.77)	.20	.04
Digit Symbol-Oral	69.33 (10.79)	76.61 (13.06)	65.35 (14.82)	**.023**	**.08**
BNT-English (/60)	51.63 (4.63)	48.83 (8.15)	36.69 (4.28)	**.001****	**.43**
FAS Fluency - English	39.86 (9.37)	40.47 (13.46)	33.91 (10.40)	.074	.06
Animals - English	24.22 (6.13)	21.67 (5.82)	21.26 (5.12)	.097	.05
FAS Fluency - French	---	28.24 (10.03)	---	---	---
BNT - French (/60)	---	36.82 (10.02)	---	---	---
Animals – L2		18.45 (6.42)	14.70 (3.62)	**.042***	**.11**

Notes: 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. English-French bilinguals were older than Arabic-English bilinguals. Although all groups were university students the Arabic-English bilinguals had lower education than the other groups. Arabic-English bilinguals performed worse on the MoCA, Stroop2, and BNT-English than the other two groups, and worse on the WCST, Stroop3, FAS and Animals-English, and Digit Symbol-Oral than English-French bilinguals. Monolinguals scored lower on the letter # sequencing than English-French bilinguals.

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

	English Monolingual	English-French Bilingual	Arabic-English Bilingual	Probability	Partial eta squared (n^2_p)
L2 Age of Acquisition	6.67 (2.39)	4.65 (3.23)	4.61 (3.31)	.96	.00
L2 Age of Fluency	----	10.16 (3.34)	9.22 (4.18)	.33	.20
English Proficiency Rating					
Listening	4.89 (0.31)	4.94 (0.23)	4.86 (0.34)	.31	.02
Reading	4.95 (0.23)	4.94 (0.23)	4.73 (0.45)	**.022**[a]	**.09**
Speaking	5.00 (0)	4.94 (0.23)	4.73 (0.45)	**.022**[a]	**.09**
Writing	4.95 (0.23)	4.92 (0.28)	4.47 (0.67)	**.001**[a]	**.18**
L2 Proficiency Rating					
Listening	1.77 (0.43)	4.58 (0.50)	4.91 (0.28)	**.004**[b]	**.13**
Reading	1.74 (0.51)	4.56 (0.50)	4.61 (0.50)	.61	.004
Speaking	1.68 (0.48)	4.39 (0.50)	4.87 (0.34)	**<.001**[b]	**.23**
Writing	1.58 (0.50)	4.03 (0.74)	4.17 (0.78)	.39	.39
L2 use at home					
Listening	----	39.19% (33.61)	59.78% (27.94)	**.017**[b]	**.09**
Speaking	----	36.49% (40.22)	65.22% (23.52)	**.013**[b]	**.14**
Reading	----	29.05% (27.95)	20.65% (17.92)	.20	.03
Writing	----	27.70% (28.74)	19.57% (19.88)	.24	.02
L2 use at school/work:					
Listening	----	42.57% (23.73)	13.04% (18.26)	**<.001**[c]	**.20**
Speaking	----	37.16% (24.20)	15.22% (19.56)	**.001**[c]	**.18**
Reading	----	33.78% (23.72)	3.26% (11.44)	**<.001**[c]	**.36**
Writing	----	33.11% (25.72)	4.35% (12.28)	**<.001**[c]	**.30**

Notes: 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. older adults. Older adults had higher self-reported French writing abilities. [a] English-French bilinguals and English monolinguals had higher scores than Arabic-English bilinguals. [b] Arabic-English bilinguals had high scores than English-French bilinguals. [c] English-French bilinguals had higher scores than Arabic-English bilinguals

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

Measures for DMS Mean (Standard Deviation)	Group		
	Monolinguals (n=25; 16 females)	French Bilinguals (n=28; 20 females)	Arabic Bilinguals (n=23; 15 females)
1 number			
RT (ms)	621.12(101.72)	587.45(120.47)	640.71 (147.80)
Accuracy (%)	94.36(2.02)	93.91(3.34)	95.46 (1.87)
Omissions (#)	2.72(0.89)	3.39(1.26)	2.91 (1.59)
Commissions (#)	1.00(1.22)	1.14(1.33)	0.91 (1.95)
3 numbers			
RT (ms)	742.32(120.47)	717.19(144.53)	746.161 (161.65)
Accuracy (%)	94.31(4.10)	94.68(3.29)	95.51 (3.42)
Omissions (#)	0.52(0.71)	0.64(0.73)	0.78 (1.35)
Commissions (#)	2.04(2.94)	1.79(1.93)	2.35 (3.26)
5 numbers			
RT (ms)	796.18(124.69)	775.37(136.37)	810.60 (164.87)
Accuracy (%)	92.67(5.53)	90.75(8.35)	93.09 (5.15)
Omissions (#)	1.16(1.43)	1.21(1.47)	1.48 (3.15)
Commissions (#)	3.32(3.23)	3.39(3.90)	2.65 (3.24)

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.

Table 4: *Behavioral performance in the n-back task for each condition and group.*

Measures for n-back Mean (Standard Deviation)	Group Monolinguals (n=32; 25 females)	French Bilinguals (n=31; 22 females)	Arabic Bilinguals (n=23; 15 females)
0-back			
RT (ms)	386.97 (47.83)	382.51 (58.89)	428.06 (89.26)
Overall Accuracy (%)	98.93 (0.66)	98.75 (1.23)	98.46 (1.08)
Target Accuracy (%)	97.24 (1.67)	96.72 (3.09)	95.87 (3.44)
Omissions (#)	0.13 (0.42)	0.42 (1.39)	1.10 (2.21)
Commissions (#)	0.28 (5.22)	0.29 (0.64)	0.29 (0.56)
1-back			
RT (ms)	444.60 (60.33)	447.36 (82.66)	485.58 (70.33)
Overall Accuracy (%)	97.26 (2.71)	98.01 (2.85)	96.96 (2.19)
Target Accuracy (%)	92.34 (8.21)	92.20 (8.08)	91.98 (6.74)
Omissions (#)	3.06 (5.22)	3.35 (5.07)	3.71 (4.37)
Commissions (#)	0.34 (0.60)	1.00 (1.31)	0.67 (0.80)
2-back			
RT (ms)	497.50 (57.08)	479.50 (80.48)	517.44 (80.14)
Overall Accuracy (%)	86.67 (4.91)	87.31 (5.23)	87.91 (2.71)
Target Accuracy (%)	70.83 (16.27)	72.31 (17.02)	76.11(7.96)
Omissions (#)	16.90 (9.82)	15.48 (10.74)	13.81 (4.97)
Commissions (#)	6.50 (2.91)	6.22 (2.39)	7.43 (3.06)

Notes: Values given are means with standard deviations.

Table 5: *Summary of ERP results*

ERP component	Condition Effects	Language Effects
DMS Task		
P2	Medium > high and low	n.s.
N2	Low < medium < high	Monolinguals > English-French and Arabic-English bilinguals
P3b	**Frontal:** Low and medium > high	**Frontal:** English- French bilinguals > Monolinguals
	Parietal: Low > medium > high	**Parietal:** n.s.
N-back Task		
P2	Latency: n.s.	Latency: Arabic-English > monolinguals
	Amplitude: low < medium < high	Amplitude: n.s.
N2	Low > medium > high	n.s.
P3b	**Frontal:** Low < medium < high	**Frontal:** English-French bilinguals > Arabic-English bilinguals and monolinguals
	Parietal: Low < medium and high	**Parietal:** n.s.

Notes: DMS = delayed matching-to sample n.s. = no significant differences

Summary

Research examining the influence of bilingualism on cognitive functioning has been controversial. Many studies have observed a bilingual advantage in several cognitive domains such as inhibition (Bialystok et al., 2008; Carlson & Meltzoff, 2008), executive control (Badzakova-Trajkov, 2008; Prior & Gollan, 2011), cognitive control (Kousaie & Phillips, 2017), and task switching (López Zunini et al., 2019). Nevertheless, several studies have been unable to replicate results showing an association between bilingualism and cognitive advantages (e.g., Duñabeitia et al., 2013; Gathercole et al., 2014; Goldman et al., 2014; Kousaie & Phillips, 2017; Nichols, Wild, Stojanoski, Battista, & Owen, 2020; Paap & Greenberg, 2013). Although inconsistencies have also been identified in working memory (e.g., Blom et al., 2014; Engel de Abreu and Abreu, 2011; Kudo and Swanson, 2014; Morales et al., 2013), meta-analyses have suggested that bilinguals may exhibit enhanced working memory capacity compared to monolinguals (Grundy & Timmer, 2017; Linck et al., 2014).

Several limitations in bilingualism research may explain the mixed findings. One limitation is that most studies rely on behavioral measures to examine the so-called bilingual advantage in working memory. Additionally, studies often compare participants with different second languages (e.g., English-French vs English-Russian) or languages which are linguistically similar (e.g., English vs French). Few studies have examined the influence of bilingualism on working memory in older adults. Because of these limitations, it is unknown if: 1) bilingualism influences processing associated with working memory, as indexed by event-related potentials (ERPs); 2) if the influence of bilingualism is more pronounced in older adults, and 3) if Arabic-English bilinguals display enhanced working memory capacity and processing compared to English monolinguals and English-French bilinguals.

To address these questions, the present study recorded ERPs to complement more traditional behavioral measures used to examine the influence of bilingualism on working memory performance and functioning. Although previous research has observed ERP differences between monolinguals and bilinguals, the influence of bilingualism on ERPs associated with working memory remains unknown.

Further considerations were made when recruiting participants to control for language proficiency. Many studies have not controlled for factors such as the age of fluency of their bilingual participants, which second language the bilingual is proficient in, and whether monolingual participants are "true" monolingual. Therefore, to address these limitations, our English-French bilinguals were required to be proficient in both English-French before the age of 13, and English monolinguals could only report "very little ability"[8] in a second language. To compare another language which is less similar to English than French, a sample of Arabic-English young adult bilinguals were also recruited. Most studies do not examine whether linguistic distance influences whether bilingual advantages are observed. By including group of Arabic-English bilinguals, we were able to examine if ERP and cognitive differences observed between monolinguals and bilinguals vary as a function of linguistic distance.

Summary of Part 1

Part 1 was designed to examine whether ERPs are more sensitive at detecting group differences between young adult monolinguals and bilinguals than behavioral measures alone. The purpose was to examine if English-French bilinguals had enhanced working memory capacity and/or differences in working memory functioning compared to monolinguals.

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[8] Participants were asked to rate their knowledge of languages they knew. The rating ranged from one to five, with one meaning "no ability at all" and five meaning "native-like ability". This rating is described in the methodology of all papers.

Participants completed an n-back task in Study 1 and a delayed matching-to-sample task in Study 2. In the n-back participants had to respond when the number presented matched the number from *n* times before (i.e., 0-, 1-, or 2-back). The delayed matching-to-sample task required participants to memorize a memory array, a few seconds later participants responded to a target stimulus identifying if the target matched one of the numbers presented in the memory array. The delayed matching-to-sample task had three levels of difficulty (1, 3, or 5 numbers).

In both Study 1 and Study 2, bilinguals did not outperform monolinguals in terms of accuracy or reaction time. Despite similar performance measures, ERPs differed between English monolinguals and English-French bilinguals. In both the delayed matching-to-sample and n-back tasks, bilinguals exhibited larger P3b amplitudes compared to monolinguals. In the delayed matching-to-sample task, bilinguals also exhibited a reduced earlier negativity (N2), and a later reduced negative slow wave. The ERP differences could be interpreted as reflecting the availability of additional cognitive resources and as a result, reduced effort needed for task completion. Because young adults performed well on both the delayed matching-to-sample and n-back tasks with an overall accuracy above .85, reporting a bilingual advantage is difficult.

Summary of Part 2

Part 2 of this work was designed to investigate the influence of both age and bilingualism on working memory and the neural activity underlying working memory. The study was integrated into the current work because no study has examined the interaction of age and bilingualism on working memory using ERPs. To examine this interaction, a sample of older adult English monolinguals and English-French bilinguals completed both the n-back (Study 3) and delayed matching-to-sample (Study 4) tasks presented in Part 1. We predicted that older adult bilinguals would outperform monolingual older adults because the bilingual advantage may offset age-related cognitive decline in working memory.

In Study 3 (n-back), ERP differences were observed between monolinguals and bilinguals even though the groups did not differ in accuracy or reaction time. In this task, bilinguals exhibited larger P3b amplitudes compared to monolinguals. Larger P3b amplitudes in bilinguals could suggest differences in cognitive processing because of bilingualism or additional resources available to bilinguals during task completion. When examining age group differences, older adults had similar accuracy but increased reaction time compared to young adults. The older adults exhibited different ERP patterns than young adults, with increased activity at lower loads of difficulty and reduced activity during the more difficult conditions. This activation suggests that older adults recruit additional brain regions during the easier conditions of a working memory task to maintain high performance, but have fewer resources available to complete the difficult conditions.

Similar to Study 3 (n-back), in Study 4 (delayed matching-to-sample), monolinguals and bilinguals achieved similar behavioral performance in the delayed matching-to-sample task while exhibiting large ERP differences. Bilinguals exhibited smaller N2 amplitudes but larger P2 and P3b amplitudes than monolinguals. Group ERP differences may reflect enhanced attentional allocation (larger P2) in bilinguals requiring reduced effort (smaller N2) and having more resources available to complete the task (larger P3b) than monolinguals.

Although reaction time was overall longer in older than young adults, there were no accuracy differences due to age group. Despite similar behavioral responses, ERPs differed between young and older adults in the delayed matching-to-sample task. Older adults exhibited larger P2 amplitudes (in the high load condition), smaller N2 amplitudes, and larger P3b amplitudes (in the medium and high load condition). Older adults also displayed a more negative late slow wave than young adults that occurred in conjunction with increased reaction time. Given the similar ERP waveforms between older adults and bilinguals, these results are difficult to interpret. Age group ERP differences during only the difficult tasks may reflect the use of compensatory mechanisms by older adults to maintain similar performance to young adults during the difficult conditions. Additionally, older adults displayed a long-lasting positive beginning at the time of the P2. This positivity could be associated with cognitive effort and may explain the similar amplitudes to bilinguals. In bilinguals, ERP differences may be associated with differences in cognitive processing compared to monolinguals. As mentioned, in the absence of performance differences between monolinguals and bilinguals, reporting a bilingual advantage in working memory processing is difficult.

With respect to age-group differences, the current results reflect older adults recruiting additional brain regions to compensation for age-related cognitive changes during the n-back. In the n-back, older adults exhibited increased P3b amplitude in the 1-back condition compared to the 0-back condition, but decreased amplitude in the 2-back compared to the 1-back. Furthermore, compared to young adults, older adults had larger overall P3b amplitudes in frontal regions during the 0- and 1-back, and smaller P3b amplitudes in parietal regions during the 2-back. Following the Compensation-Related Utilization of Neural Circuits Hypothesis (CRUNCH; Reuter-Lorenz and Lustig, 2005), older adults recruited additional resources at lower levels of task difficulty. Older adults may exhibit lower amplitudes during the most difficult task (2-back) because they are unable to recruit additional resources at that level of difficulty. During the more difficult task, the older adults’ available resources may have reached ceiling, leading to insufficient processing for this task. These findings may also support the Posterior-to-Anterior

Shift in Aging (Davis, 2008) hypothesis indicating that older adults recruit additional frontal regions to compensate for declines in parietal regions. In the DMS task, the ERP waveforms do not follow any specific aging theory or model. This limitation could be related to the ceiling effects in performance measures across all three working memory loads.

Both the ERP age and language group differences varied between the delayed matching-to-sample and n-back tasks. Possible reasons for these differences are discussed in implications and future research.

Summary of Part 3

The last part of the presented work intended to expand on existing research in current bilingualism research. Many researchers often compare participants proficiency in Indo-European languages, such as English and French. The purpose of the fifth study was to determine whether the nature of bilingualism may influence whether differences between monolinguals and bilinguals are observed. To examine this, young adult English monolinguals and English-French bilinguals were compared to a sample of Arabic-English bilinguals. Arabic was chosen because this language is much more linguistically different from English than French. Because of the linguistic distance between Arabic and English, being bilingual in these two languages may require more resources and cognitive effort to manage and switch between them than managing and switching between English and French.

Study 5 compares the ERPs of young adult Arabic-English bilinguals to English monolinguals and English-French bilinguals during both the delayed matching-to-sample and n-back tasks. Behavioral performance did not differ in either task between the three groups. In the delayed matching-to-sample task, monolinguals exhibited smaller N2 amplitudes compared to both bilingual groups, and smaller P3b amplitudes compared to English-French bilinguals. In the n-back, English-French bilinguals displayed larger P3b amplitudes than both English monolinguals and Arabic-English bilinguals. P3b amplitude did not differ between Arabic-English bilinguals and monolinguals in either task. During a task that activates the phonological loop (delayed matching-to-sample), monolinguals may require more effort to complete the task (reflected by larger N2s). Larger P3b amplitudes in the English-French bilinguals may indicate they have more resources available than monolinguals and Arabic-English bilinguals in the n-back task. These results may suggest that conflicting findings across bilingualism studies could be due in part to the linguistic distance between the languages under study. However, given that there were English proficiency differences between groups future research should replicate these findings. Furthermore, given that language differences varied between tasks it is possible that effects of bilingualism may be task-dependent.

Implications and Future Research

ERP differences by language and age group were observed in both the delayed matching-to-sample and n-back tasks. However, these ERP group differences were not consistent between the two working memory tasks. In the delayed matching-to-sample task, both bilingual groups (English-French and Arabic-English) exhibited smaller N2 amplitudes compared to monolinguals. In the n-back task, N2 amplitude did not differ between the three language groups. Regarding age, in the delayed matching-to-sample task, older adults had similar waveforms to the bilinguals (more positive waveforms overall). On the other hand, in the n-back, older adults displayed ERPs that were consistent with the CRUNCH model with increased activity in easier conditions but decreased activity in difficult conditions compared to young adults. These task differences could arise because the tasks require different strategies to complete or because the tasks may measure different components of working memory. The delayed matching-to-sample task (Sternberg) is a span task that requires the use of a phonological loop and articulatory rehearsal to maintain information in working memory (Baddeley, 2000; Germano & Kinsella, 2005). The n-back, however, is a dual-task paradigm which activates many processes simultaneously (e.g., encoding, updating of information, matching the stimulus to the one *n*-times before) (Watter et al., 2001). Taken together, these results suggest that the components of working memory may be affected differently by increased age and bilingualism. It is difficult to determine which components of working memory are responsible for the group differences in these tasks. For example, it would be expected that there would be more rehearsal in the delayed matching-to-sample than n-back task, but there would be more updating of information in the n-back than delayed matching-to-sample task. Future research should be cautious when comparing results from tasks that activate different components of working memory.

Bilingualism Research. Throughout the presented studies, bilingualism influenced the ERPs associated with working memory. These results have many implications for future studies on bilingualism. Importantly, monolinguals and bilinguals displayed different ERPs in the absence of behavioral differences. The absence of behavioral differences between young adult monolinguals and bilinguals could be attributed to ceiling effects on different tasks. This explanation, however, cannot be applied to the older adult data. Older adult bilinguals also did not differ behaviorally from older adult monolinguals.

While the behavioral data did not differ between monolinguals or bilinguals for either age group, ERP measures of cognitive processing did. Different cognitive strategies used to maintain performance might explain why behavioral measures do not vary but ERP measures differed between groups. It is possible, for example, that monolinguals used a cognitive strategy that required additional effort to maintain performance. The use of different cognitive strategies might explain the monolinguals' smaller amplitude P3b but larger N2 amplitude. Another possible account for the lack of behavioral differences is that the bilingual advantage is most observable when task demands are high (Sullivan et al., 2016). In difficult tasks, additional effort may not be sufficient to allow for the performance of monolinguals to be similar to that of bilinguals. It remains to be determined whether ERP differences reflect behavioral advantages in bilinguals when working memory tasks are more difficult. Future research should examine ERP differences between monolinguals and bilinguals when task demands are very high, resulting in lower accuracy. This methodological change might help determine whether there is a bilingual advantage in working memory.

We also observed differences in ERPs between the bilingual groups. English-French bilinguals had larger P3b amplitudes than monolinguals across both tasks (delayed matching-to-sample and n-back). However, when taking into consideration the Arabic-English bilinguals, this groups ERPs did not differ from monolinguals in either task, and their P3b was smaller than English-French bilinguals in the n-back task. The presence of differences between monolinguals and only English-French bilinguals' ERPs should be a cautionary note for future studies. This finding shows that ERP language group differences may be restricted to specific languages or contexts. As mentioned, many researchers do not control the language of proficiency of their participants. For example, several studies will compare monolinguals to bilinguals with several L2s or compare two Indo-European languages. The current work suggests that future research should be more cautious when comparing bilinguals of different languages.

We predicted that Arabic-English bilinguals would have larger ERP differences from monolinguals than English-French bilinguals. This hypothesis was made because Arabic shares less similarity to English than French. While English and French are from the same language family (i.e., on the same family tree) and share many similarities, Arabic resides on a different tree and shares fewer similarities with English and French. Arabic-English bilinguals, however, did not exhibit larger P2 and P3b or smaller N2 amplitudes compared to English-French bilinguals. Even though we did not observe the expected results between the bilingual groups and monolinguals, we found varied results depending on both the bilingual group and the task. Thus, these results suggest that differences between languages may influence the processes involved with working memory. Future researchers should use more strict control of participants' language backgrounds to have a better understanding of the effects of bilingualism on cognition. Several researchers have suggested that a combination of methodologies (e.g., neuroimaging methods, more sophisticated statistical approaches, standardized measures to assess fluency in both languages) should be used to identify under what circumstances a bilingual advantage may occur (Kousaie & Taler, 2015; Treccani & Mulatti, 2015; van Heuven & Coderre, 2015). In addition to different methodological tools, researchers should use different selection procedures for language(s) of fluency in bilingual and monolingual participants.

Aging. Although there were differences in several ERP components (i.e., P2, N2, P3b, late slow-wave) between young and older adults, a group difference in accuracy was not apparent for either the delayed matching-to-sample or the n-back task. The ERP differences between young and older adults may reflect additional resources and effort (compensatory mechanisms) used by older adults to maintain similar performance to young adults. Future research should replicate these findings with increased task difficulty (e.g., 3-back or 7 numbers in the delayed matching-to-sample) to examine if ERP differences occur alongside behavioral differences. A problem with increasing task difficulty in the n-back, is that a 3-back might be too challenging for participants to complete successfully. Accuracy achieved may thus be at or below chance level. ERPs and accuracy would thus be difficult to interpret if the task is too difficult.

ERP differences in older adults between the two tasks (n-back and delayed matching-to-sample) could be because of task difficulty. Older adults achieved high accuracy in the delayed matching-to-sample task (< .90 for all conditions) whereas target accuracy in the 2-back was only around .71 in older adults. The delayed matching-to-sample task was thus easier and therefore may have required less effortful processing and fewer resources to complete compared to the n-back. Although both the delayed matching-to-sample tasks involve working memory the processes involved are not identical. Thus, ERP differences between the tasks may also reflect varying rates of decline in these processes with increased age.

Bilingualism and Aging. Part 2 of this thesis examined whether bilingual older adults display enhanced working memory functioning and different ERPs than monolingual older adults. Behavioral differences were not observed between monolingual and bilingual older adults; there were also no interactions between language and age. Thus, an advantage for bilingual older adults was not found. While we found an overall influence of language on ERPs (e.g., larger P3b amplitudes in bilinguals compared to monolinguals in both young and older adults), these differences were not moderated by age or task difficulty. These findings suggest that while bilinguals may display different ERPs than monolinguals, a bilingual advantage in working memory is not present. Different ERPs between language groups may suggest that bilinguals use different cognitive processing strategies to complete the tasks. It would be of interest to examine whether the different processing strategies result in enhanced performance. To examine this, researchers could either increase the level of task difficulty to maximize participant capacity or complete the testing on adults with lower cognitive capacity. Although some researchers have studied the influence of bilingualism on cognitive impairment (e.g., Bialystok et al., 2007; Chertkow et al., 2010; Craik et al., 2010), to my knowledge, this research has not included ERPs.

Limitations

It is important to note some limitations in the aforementioned studies. Importantly, there were significant language usage differences between Arabic-English and English-French bilinguals. Arabic-English bilinguals used Arabic more often at home for communication but used Arabic less often at school/work than the English-French bilinguals used French. For example, Arabic-English bilinguals listened to and spoke Arabic 30% more often at home than English-French bilinguals listened to and spoke French at home. At school/work, English-French bilinguals used French almost 30% more often across all modalities (listening, reading, speaking, and writing) than Arabic bilinguals used Arabic at school/work. The context in which these bilinguals use their language may influence their level of proficiency in both languages. Although ERP differences between the two bilingual groups were observed in the n-back, the results should be replicated with groups that have similar language usage.

In all of the studies presented the majority (approximately 70%) of participants were women. One concern associated with this skew is the generalizability of the current results to other studies and the general population. Nevertheless, a recent review by Grissom & Reyes (2018) examined whether executive functions including working memory are influenced by sex differences. These authors reported that there is little support for significant sex differences in executive functioning. They also noted that differences observed between males and females is likely related to different strategies employed rather than a difference in ability. Thus, even with the current study being comprised of mainly women, our results are still likely generalizable. Another limitation was the high degree of overlap of participants between the paradigms. The sample of young and older adults in the n-back study was similar to that of the DMS study. This is a limitation because the obtained results could be specific to the sample being studied and may reduce the generalizability of results. The findings from these publications are thus not independent and the results should not be interpreted as multiple instances of the same outcomes. Future researchers should be cautious when completing meta-analysis using these studies to avoid over-representing the same samples and biasing outcomes.

Another limitation of the studies is the similar behavioral measures among monolingual and bilingual participants on both the delayed matching-to-sample and n-back tasks. A traditional G-power analysis would suggest that differences between the groups were not observed because of insufficient power. G-power analyses assume that each participant is measured once per condition. In the present studies, however, participants completed over 100 trials in all conditions. A recent study by Goulet & Cousineau (2019) designed a statistical power method that uses both the number of replications (i.e., trials) and the between-measurement correlation of the replications to provide the “effective” number of participants for any given study. Using this method, the “effective” number of participants per group was 23 for the n-back and 27 for the delayed matching-to-sample. Based on this calculation, the results in current thesis are unlikely to be attributed to insufficient power.

The lack of behavioral differences between monolinguals and bilinguals makes the interpretation of ERP group differences challenging. The ERP language group differences could reflect 1) additional available resources and less effort needed by the bilinguals for task completion; 2) different cognitive processes or strategies used for task completion; or even as 3) inefficient processing in bilinguals because the monolinguals performed as well as bilinguals while apparently exerting less effort.

Strengths

The above-mentioned studies are the first studies to examine working memory processing in monolinguals and bilinguals using ERPs. The observation that ERPs can differentiate between monolinguals and bilinguals during working memory tasks despite the two groups performing similarly on behavioral measures is a novel finding. This finding provides evidence that monolinguals and bilinguals may use different processing strategies while engaged in the same task. This thesis also reinforces an often-identified problem with the strict use of behavioral measures. Interpreting behavioral data requires that the researcher infer the cognitive processes that led to the actual response. Most cognitive models assume that a series of processes, or "stages" intervene between the onset of the stimulus and the later overt response. Group differences could result from changes in processing during any of these hypothetical stages. A failure to observe group differences on performance does not imply that the processing within each of the various hypothetical stages was identical. Again, different strategies can be employed to successfully maintain performance. The processes resulting in a final response have a past, a present, and a future. The advantage of measures such as ERPs is that they can monitor processing before, at the time of, and following the actual response.

Study 5 was the first to examine whether a bilingual advantage is more pronounced in Arabic-English bilinguals during two working memory tasks. These novel results show that bilingual participants' languages of proficiency may influence ERP differences between monolinguals and bilinguals. By incorporating a language that is more linguistically different from English than French, we provide evidence that cognitive benefits of bilingualism may be influenced by a factor (i.e., linguistic distance) that is often overlooked. These results suggest that conflicting findings across bilingualism studies may be due in part to the linguistic distance between the languages under study. However, given that there were English proficiency differences between groups future research should replicate these studies. Another possibility is that differences between monolinguals and bilinguals are task-dependent. These findings can help improve future research by suggesting different methodological tools and guiding participant recruitment methods.

Conclusions

These studies provide evidence that bilinguals may display different ERPs than monolinguals during a working memory task, in the absence of a behavioral advantage. These ERP differences were, however, not revealed for all groups of bilinguals. Linguistic distance between the languages influenced whether monolinguals and bilinguals differed. Arabic-English bilinguals displayed similar ERPs compared to monolinguals and bilinguals despite being proficient in a language less similar to English than French is. The English-French bilingual differences were observed in older adults, but there was no interaction between language and age. Thus, bilingual advantages in working memory are not more pronounced in older adults despite ERP differences.

In sum, the present work demonstrates that working memory processing may differ between monolinguals and bilinguals in the absence of a bilingual advantage. Using behavioral measures alone may not be sensitive enough to observe these group differences. Although ERP differences were present between monolinguals and bilinguals, no bilingual advantage in working memory functioning was observed in either young or older adult English-French bilinguals or young adult Arabic-English bilinguals.

References

Baddeley A (2000) The episodic buffer: a new component of working memory? Trends in *Cognitive Sciences*, 4, 417–423. https://doi.org/10.1016/S1364-6613(00)01538-2

Badzakova-Trajkov, G., 2008. A behavioural and functional imaging investigation of Stroop task performance in late proficient bilinguals. Doctoral Dissertation, ResearchSpace@ Aukland.

Bialystok, E., Craik, F., & Luk, G. (2008). Cognitive control and lexical access in younger and older bilinguals. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *34*(4), 859. https://doi.org/10.1037/0278-7393.34.4.859

Bialystok, E., Craik, F. I., & Freedman, M. (2007). Bilingualism as a protection against the onset of symptoms of dementia. *Neuropsychologia*, *45*(2), 459-464. https://doi.org/10.1016/j.neuropsychologia.2006.10.009

Blom, E.,Küntay,A. C., Messer, M.,Verhagen, J.,&Leseman, P. (2014). The benefits of being bilingual:Working memory in bilingual Turkish–Dutch children. *Journal of Experimental Child Psychology, 128,* 105–119.

Carlson, S. M., & Meltzoff, A. N. (2008). Bilingual experience and executive functioning in young children. *Developmental Science,* 11(2), 282-298.

Chertkow, H., Whitehead, V., Phillips, N., Wolfson, C., Atherton, J., & Bergman, H. (2010). Multilingualism (but not always bilingualism) delays the onset of Alzheimer disease: evidence from a bilingual community. *Alzheimer Disease & Associated Disorders*, 24(2), 118-125. https://doi.org/10.1097/WAD.0b013e3181ca1221

Craik, F. I., Bialystok, E., & Freedman, M. (2010). Delaying the onset of Alzheimer disease: Bilingualism as a form of cognitive reserve. *Neurology*, 75(19), 1726-1729. https://doi.org/10.1212/WNL.0b013e3181fc2a1c

Davis, S.W., Dennis, N. A., Daselaar, S. M., Fleck, M. S., & Cabeza, R. (2007). Que pasa? the posterior–anterior shift in aging. *Cerebral Cortex,* 18(5), 1201–1209. 10.1093/cercor/bhm155.

de Bruin, A., Bak, T. H., & Della Sala, S. (2015). Examining the effects of active versus inactive bilingualism on executive control in a carefully matched non-immigrant sample. *Journal of Memory and Language*, 85, 15-26.

Duñabeitia, J. A., Hernández, J. A., Antón, E., Macizo, P., Estévez, A., Fuentes, L. J., & Carreiras, M. (2014). The inhibitory advantage in bilingual children revisited. *Experimental Psychology*. https://doi.org/10.1027/1618-3169/a000243

Engel de Abreu, P. M. (2011).Working memory in multilingual children: Is there a bilingual effect? *Memory, 19*(*5*), 529–537. https://doi.org/10.1080/09658211.2011.590504

Gathercole, V. C., Thomas, E. M., Kennedy, I., Prys, C., Young, N., Vinas Guasch, N., Roberts, E. J., Hughes, E. K., & Jones, L. (2014). Does language dominance affect cognitive performance in bilinguals? Lifespan evidence from preschoolers through older adults on card sorting, Simon, and metalinguistic tasks. *Frontiers in Psychology, 5,* 11. doi:10.3389/fpsyg.2014.00011

Germano, C., & Kinsella, G. J. (2005). Working memory and learning in early Alzheimer's disease. *Neuropsychology Review*, 15(1), 1-10.

Goldman, M. C., Negen, J., & Sarnecka, B. W. (2014). Are bilingual children better at ignoring perceptually misleading information? A novel test. *Developmental Science,* 17(6), 956-964.

Goulet, M. A., & Cousineau, D. (2019). The power of replicated measures to increase statistical power. *Advances in Methods and Practices in Psychological Science*, 2(3), 199-213.https://doi.org/10.1177%2F2515245919849434

Grissom, N. M., & Reyes, T. M. (2019). Let's call the whole thing off: evaluating gender and sex differences in executive function. *Neuropsychopharmacology*, *44*(1), 86-96.

Grundy JG and Timmer K (2017) Bilingualism and working memory capacity: A comprehensive meta-analysis. *Second Language Research*, 33, 325–340. https://doi.org/10.1177/0267658316678286.

Kousaie, S., & Phillips, N. A. (2017). A behavioural and electrophysiological investigation of the effect of bilingualism on aging and cognitive control. *Neuropsychologia*, *94*, 23-35.

Kousaie, S., & Taler, V. (2015). The bilingual advantage: Elusive but worth the effort? *Cortex: A Journal Devoted to the Study of the Nervous System and Behavior*, 73, 338–339. https://doi.org/10.1016/j.cortex.2015.07.019

Kudo, M., & Swanson, H. L. (2014). Are there advantages for additive bilinguals inworkingmemory tasks? *Learning and Individual Differences, 35,* 96–102. https://doi.org/10.1016/j.lindif.2014.07.019

Linck, J.A., Osthus, P., Koeth, J.T., Bunting, M.F., 2014. Working memory and second language comprehension and production: A meta-analysis. *Psychonomic Bulletin & Review*, 21, 861–883. https://doi.org/10.3758/s13423-013-0565-2

López Zunini, R., Morrison, C., Kousaie, S., Taler, V., 2019. Task switching and bilingualism in young and older adults: A behavioral and electrophysiological investigation. *Neuropsychologia,* 133, 107186. https://doi.org/10.1016/j.neuropsychologia.2019.107186

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

Paap, K. R., & Greenberg, Z. I. (2013). There is no coherent evidence for a bilingual advantage in executive processing. *Cognitive Psychology*, *66*(2), 232-258. https://doi.org/10.1016/j.cogpsych.2012.12.002

Prior, A., & Gollan, T. H. (2011). Good language-switchers are good task-switchers: Evidence from Spanish–English and Mandarin–English bilinguals. *Journal of the International Neuropsychological Society*, *17*(*4*), 682–691. https://doi.org/10.1017/S1355617711000580

Reuter-Lorenz, P. A., & Lustig, C. (2005). Brain aging: reorganizing discoveries about the aging mind. *Current Opinion in Neurobiology*, 15(2), 245-251. https://doi.org/10.1016/j.conb.2005.03.016

Rosselli, M., Ardila, A., Santisi, M. N., Arecco, M. D. R., Salvatierra, J., Conde, A., & Lenis, B. O. N. I. E. (2002). Stroop effect in Spanish–English bilinguals. *Journal of the International Neuropsychological Society*, *8*(6), 819-827. https://doi.org/10.1017/S1355617702860106

Sullivan, M. D., Janus, M., Moreno, S., Astheimer, L., & Bialystok, E. (2014). Early stage second-language learning improves executive control: Evidence from ERP. *Brain and Language*, *139*, 84-98. https://doi.org/10.1016/j.bandl.2014.10.004

Treccani, B., & Mulatti, C. (2015). No matter who, no matter how… and no matter whether the white matter matters. Why theories of bilingual advantage in executive functioning are so difficult to falsify. *Cortex: A Journal Devoted to the Study of the Nervous System and Behavior,* 73, 349–351. https://doi.org/10.1016/j.cortex.2015.07.015

Watter, S., Geffen, G. M., & Geffen, L. B. (2001). The n-back as a dual-task: P300 morphology under divided attention. *Psychophysiology*, 38(6), 998-1003. https://doi.org/10.1111/1469-8986.3860998

Zahodne, L. B., Schofield, P. W., Farrell, M. T., Stern, Y., & Manly, J. J. (2014). Bilingualism does not alter cognitive decline or dementia risk among Spanish-speaking immigrants. *Neuropsychology*, 28(2), 238. doi:10.1037/neu0000014.

Appendix A: Description of Cognitive Tasks

Delayed matching-to-sample (Sternberg task): Participants are presented with a set of visual stimuli they are asked to memorize (memory array). The memory stimulus is then replaced by a single stimulus (test stimulus). The participants are then asked to identify if the single stimulus was present in the previous presented memory array. The size of the memory array can vary changing the difficulty of the task. An example is as follows: a set of 5 numbers is presented on the screen (e.g., 56879) this is followed by a single number (e.g., 3); participants are asked to identify if the 3 was present in the memory set by pressing a button. This task is used to study working memory.

Flanker task: In the standard version of this task, a central target item is presented with two or more irrelevant flankers (which can be congruent or incongruent). For example, participants may be shown a series of arrows and must indicate the direction of the target arrow. In the congruent condition, a target arrow is flanked at each side by two nontarget arrows, which point in the same direction (e.g., <<≤<< or >>≥>>). In the incongruent condition, the target arrow is flanked by arrows which point in the opposite direction (e.g., <<≥<< or >>≤>>). In the neutral condition, the target arrow is presented without any other arrows (e.g., --≥-- or --≤--). This task is a measure of the processes involved with inhibition, conflict monitoring/conflict resolution.

Letter-Number sequencing task: Participants are asked to recall a series of mixed numbers and letters in numerical and alphabetical order. Participants are tested up to their maximum capacity (maximum number of stimuli that they can successfully recall). This task assesses working memory capacity.

N-back task: Participants are presented a series of single stimuli continuously. For each stimulus they are required to identify if it matches the stimulus from *n* trials before. For example, in an n-back presenting numbers the participants may be required to complete three conditions (0-, 1-, and 2-back). In the 0-back the participant would be asked to respond when a 0 is presented (e.g., 23028045). In the 1-back participants would respond when the stimulus is the same as the number in the trial n-1 (e.g., 23446778). For the 2-back, participants would be asked to respond when the number presented matches the number from n-2 trials before (e.g., 2328387). The task requires continuous encoding, updating, and storage of each stimulus and is thus a measure of working memory.

Oddball: In this paradigm, participants are presented with frequently occurring "standards" and at rare (or "odd") times, a feature of the standard is changed to form a "deviant". The features of all incoming stimuli are compared against the features of the previously presented standard stimulus stored in sensory memory. The oddball is used to measure working memory.

Simon task: In this task, participants are asked to make a response (i.e., pressing a left or right key) to a specific characteristic of a presented stimulus (e.g., red or blue square). For example, participants will see a red or blue square on either the left or right side of a screen. The participant would be asked to press the left key when the red square appears and the right key when the blue square appears. This task consists of both congruent trials (the red square is presented on the left side; the response key and stimulus are on the same side) and incongruent (the red square is presented on the right side; the response key and stimulus are on opposite sides). The Simon task is a measure of conflict resolution, inhibition, and interference.

Span task: Participants are asked to recall a list of numbers or words. Participants are tested up to their maximum capacity (maximum number of stimuli that they can successfully recall). A common example is the digit span. The digit span consists of a forward span (i.e., the maximum number of items the participant can recall in the same order that the numbers were heard) and backward span (i.e., the maximum number of items participants can recall in the reverse order). The forward span assesses short term memory and the backward span assesses working memory.

Stroop task: Participants are asked to name the colors of x's (e.g., XXXXX), to read the color of words (e.g., RED, BLUE, GREEN), and to read the ink color of color words printed in a different color (e.g., the word "RED" printed in green ink; in this example participants would say green and not red). The purpose of this task is to examine participants' ability to inhibit the inappropriate response when the ink color and word do not match.

Task-switching: Participants are presented with two types of trials, trials where the task changes (switch trials) and trials where the task does not change (repeat trials). An example would be to present stimuli in a mixed-task block (e.g., C D C D C D) or a single-task block (e.g., C C C C C or D D D D D). In this example, performance in the mixed block is compared with the performance in the single block. This type of task measures the ability to "switch" attention between the tasks by examining cognitive control and task interference.