Attentional Control Processing in Working Memory: Effects of Aging and Bilingualism

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Abstract

Selective attention is required for working memory and is theorized to underlie the process of selecting between two active languages in bilinguals. Studies of working memory performance and bilingualism have produced divergent results and neural investigations are still in the early stages. The purpose of the current series of studies using older and younger bilingual and monolingual adults was to examine working memory processing by manipulating attentional control demands and task domain. It was hypothesized that bilinguals in both age groups will outperform monolinguals when verbal demands are low and when attentional control demands are high. Study 1 included behavioural tasks that varied by domain and attentional control. Study 2 addressed these factors by examining the neural correlates of maintenance and updating using ERPs. A third analytic approach using partial least squares (PLS) analysis was performed on the recognition data from Study 2 to assess contrasting group patterns of amplitude and signal variability using multiscale entropy (MSE). Bilingual performance was poorer than monolingual when the task involved verbal production, but bilinguals outperformed monolinguals when the task involved nonverbal interference resolution. P3 amplitude was largely impacted by attentional demands and aging, whereas language group differences were limited. Extensive language and age group differences emerged once whole brain neural patterns were examined. Bilingual older adults displayed a neural signature similar to younger adults for both amplitude and MSE measures. Older adult monolinguals did not show these patterns and required additional frontal resources for the difficult spatial update condition. Younger bilinguals showed long-range, frontal-parietal MSE patterns for updating in working memory. These results are consistent with the interpretation of brain functional reorganization for bilingual working memory processing and may represent adaptations to a top-down attentional control mechanism.

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Introduction

There are several challenges that accompany any investigation of working memory. The first, at its most fundamental form is defining what working memory is and how it may differ from, yet also integrate with, other dominant cognitive constructs (Eriksson, Vogel, Lansner, Bergström, & Nyberg, 2015), such as the executive control system, selective attention, and long-term memory or knowledge/experience. A second challenge is to identify whether different domains have diverse underlying mechanisms in memory processing. Indeed, there is a long history examining memory for verbal versus nonverbal/spatial information (Baddeley, 2012). Third, attempts to synthesize behavioural and neural data to make conclusive models (D' Esposito, 2007), and interpret neural differences in the face of equivalent behaviour are problematic. Finally, there is the challenge to create lifespan models of cognitive development that incorporate the well-known declines in working memory with aging (Park & Payer, 2006).

What can bilingualism offer to research on working memory? Language and cognition are deeply intertwined in human thought (Perlovsky, 2009). With approximately half of the global population being bilingual or multilingual (Grosjean, 2010), a better understanding of bilingual memory is necessary for both the fields of working memory more generally, and bilingualism and cognition to progress. Bilingualism has been linked to both cognitive and linguistic differences from monolingualism across the lifespan (Kroll & Bialystok, 2013), however the extent to which these differences relate to memory processing is poorly understood. In addition, the underlying mechanism behind the link between lifelong bilingualism and a delayed onset of symptoms of dementia (e.g., Alladi et al., 2013; Bialystok, Craik, Freedman,

2007; Craik, Bialystok, & Freedman, 2010; Woumans et al., 2015), a disease where the primary symptom is memory loss, has not been identified.

Recently it has been proposed that selective attention may be the basis for the large body of literature showing performance differences between bilinguals and monolinguals on nonverbal conflict tasks (Bialystok, 2015; 2017), with better performance by bilinguals particularly during childhood and older adulthood. Modification to the attentional control system may arise from the consistent management of two active languages (Kroll, Dussias, Bogulski, & Valdes-Kroff, 2012), such that attentional focus is required to select the target language while avoiding the interfering, nontarget language. It was the goal of the current dissertation to further explore in a series of studies how (1) attentional control and (2) stimulus domain, i.e., verbal or nonverbal items, influence bilingual memory performance and neural processing. The study samples included younger and older adults to assess how these differences may change over the course of the lifespan. The current chapter will provide an overview of some of the major theoretical accounts and evidence pertaining to *working memory models*, *neuroscience findings for working memory*, *aging and brain functional reorganization*, and finally present *a proposed model of bilingual working memory*. Chapters 2–4 present behavioural and neural studies of bilingualism, aging, and working memory.

Working Memory Models

To begin, working memory is the temporary storage of information that is no longer present in the physical environment. Maintenance or longer storage of this information is achieved through the processes of rehearsal or mental repetition. More effortful mental operations can be applied to this information, through the processes of updating or re-sequencing, to manipulate it to achieve a desired goal (D'Esposito, 2007). Selective attention

refers to the process of focusing on goal-relevant items, while avoiding irrelevant items (Gazzaley & Nobre, 2012). Finally, executive control/function involves top-down, effortful mental operations that implement goal-directed behaviours (Diamond, 2013). Despite their operational distinctions, major theorists of working memory tend to incorporate attention and an executive system into their models, indicating a strong form of interdependence between these constructs.

One of the most prominent theories of working memory is Baddeley's multistore model (Baddeley, 1986; Baddeley & Hitch, 1974). The relevance of this model for bilingual memory is that it involves a separate store for verbal, i.e., the phonological loop, and nonverbal information, i.e., the visuospatial sketchpad. Separate systems for verbal and nonverbal memory could support predictions that language group differences could vary by domain (see Calvo, Ibáñez, & García, 2016). Baddeley proposed a central executive that has control over the actions of the two stores, and later developed an episodic buffer component to integrate domain information and provide connections to perception and long term memory (review in Baddeley, 2012). The more a working memory task depends on attentional or effortful control, as when order is manipulated in a span task, the greater the need for the central executive. In contrast to the multistore model, Cowan (1999) developed a model in which working memory relies on activation of information from long term memory that is domain general. The embedded-processes model of working memory emphasized the importance of attention, and the contents of working memory are constrained by our attentional focus or capacity and also temporal constraints. In Cowan's model, attention can be controlled by an executive system or automatic mechanisms.

A more recent method of conceptualizing the relationship between executive control, working memory, and attention is with a component process view of working memory. In this

case, working memory functions as several online processes that are called upon when required, and may include for example, selective attention, sustained attention and rehearsal, updating, or inhibition. These processes are not exclusive to working memory, and their recruitment will depend on the nature of the task or goal and the stage of memory processing (i.e., encoding, maintenance or manipulation, and retrieval). These component processes interact with the required items needed to be remembered (e.g., verbal or nonverbal stimuli; presented auditorily or visually) and the specific procedures needed to be performed (e.g., numerical, alphabetical, or associative operations) to complete a task (see Eriksson et al., 2015 for a description of this working memory model). The coordination of these processes, including their recruitment, disengagement and shifting most likely involves a central executive system similar to the one depicted in earlier models of working memory.

Another way of viewing this relationship that is not mutually exclusive with the component process view is to set selective attention as the underlying component that is crucial not only to executive control and working memory, but also to language control (see Figure 1). It is through the experience of bilingualism and management of two active languages that the process of selective attention is adapted or even enhanced via a feedback mechanism to avoid lexical interference. This enhancement of a core cognitive component can then be utilized when engaging in executive control or working memory tasks. The relationships between selective attention, working memory, and executive control are complex and are likely bidirectional. For instance, an item held in working memory can influence selective attention in a visual search task (Hernández, Costa, & Humphreys, 2012). Selective attention is also necessary to encode items in working memory (Eriksson et al., 2015). Executive control processes update the contents of working memory, allowing newly attended items to be stored and also manage

interference from irrelevant information (Szmalec, Verbruggen, Vandierendonck, & Kemps, 2011). As will be discussed below, tasks of executive control and working memory correlate highly, and this may be due to the third underlying variable of selective attention.

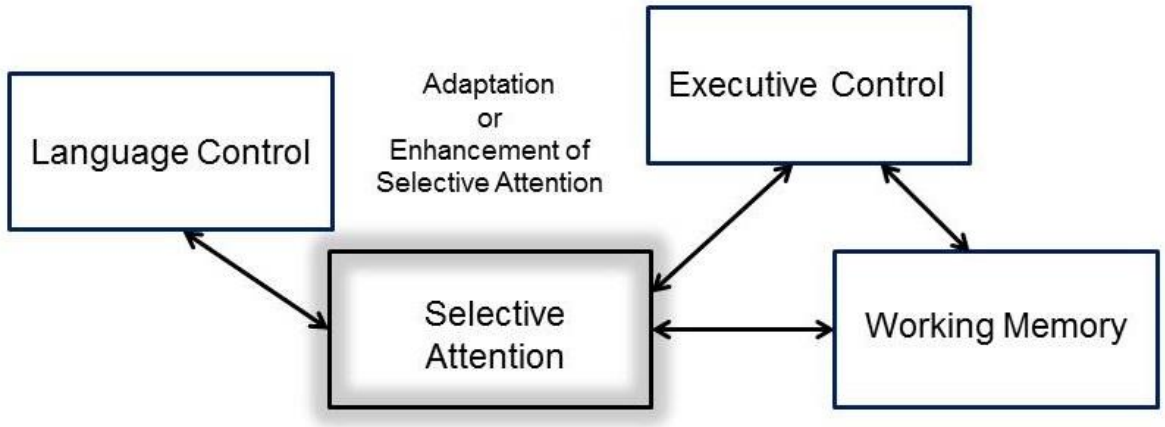


Figure 1. A proposed system for the role of selective attention in working memory, executive control, and language control.

In line with this framework, Engle and colleagues' proposed notion of working memory capacity involves maintaining activated information in attention, a process that largely relies on attentional control and crucially, the management of interference. This process has been conceptualized as the use of domain-general executive attention (Engle, Tuholski, Laughlin, & Conway, 1999; Engle, 2002), and empirical evidence supporting the view that attention underlies the relationship between working memory and executive control is given from a large-scale factor analysis comparing capacity, as measured by complex verbal and nonverbal span tasks, with executive function tasks across the lifespan, in participants aged 18 to 90 years old. The results of this study by McCabe, Roediger, McDaniel, Balota, and Hambrick (2010) indicated

that there was a stronger correlation between working memory capacity and executive function than between each construct and speed of processing. The underlying relationship between working memory capacity and executive function is interpreted as use of executive attention (see also Figure 1). Kane and Engle (2000) also showed that when high and low capacity working memory participants performed a verbal proactive interference task, high span participants outperformed low span participants under conditions of full attention but not divided attention, supporting the role of attention in working memory when dealing with interference. Thus, in spite of the considerable differences across conceptualizations, all of the models include a major component for attention in working memory.

Neuroscience Findings for Working Memory

Advances in functional neuroimaging have made it possible to investigate how the brain is involved in working memory processing. For instance, in their review Jonides et al. (2008) illustrated that all four lobes of the brain are relevant when considering the distinct stages of working/short term memory. In brief, representations of to-be-remembered stimuli are stored in cortical regions involved in their perception. The medial temporal lobe allows for information in working memory to be bound to the relevant context. Attentional control and focus are managed by a frontal-parietal network, with the frontal lobes also having a role in the effortful control of interference and memory retrieval. Along with these regions, there is also evidence for activity in the cerebellum, and the basal ganglia and striatum regions (see Eriksson et al., 2015 for review), furthering the point that working memory involves broad network interactions throughout multiple brain regions. Notably, prefrontal and parietal activation appear to be the most consistent result found across positron emission tomography (PET) and functional magnetic

resonance imaging (fMRI) studies with younger adults performing working memory and attention tasks (Cabeza & Nyberg, 2000).

Verbal and nonverbal stimuli have been shown to elicit opposing laterality effects mainly within the prefrontal cortex, but there is also evidence for this distinction within the parietal cortex (Eriksson et al., 2015). Work with fMRI and PET has shown greater left-lateralization for verbal working memory processing with nonverbal/spatial working memory being more right-lateralized or bilateral with areas of prominent right-lateralization (e.g., D'Esposito et al., 1998, Smith, Jonides, & Koeppe, 1996). When the focus is on the processes involved in working memory, studies have shown across verbal and nonverbal domains that manipulation of items in memory rather than maintenance requires increased activation in the dorsolateral prefrontal cortex (D'Esposito et al., 1998; D'Esposito, Postle, Ballard, & Lease, 1999; Eriksson et al., 2015; Glahn et al., 2002; Smith & Jonides, 1999; Wager, & Smith, 2003).

In the event-related potential (ERP) literature, in which electrical, neural activity is recorded in milliseconds through electrode placement at the scalp, rather than the time course of seconds using the blood flow related properties of fMRI, laterality effects of working memory domain can vary by waveform component and timescale. For example, Shucard, Tekok-Kilic, Shiels, and Shucard (2009) found that the pattern of activity for the scalp topography of the P3 component, which is a commonly researched positive voltage deflection occurring around 300 ms in relation to stimulus onset and is associated with working memory processing (Amin, Malik, Kamel, Chooi, & Hussain, 2015; Donchin, 1981; discussed further in Chapter 3), did not vary by verbal (letter identity) or spatial (letter location) domain but rather by the stage and effort involved in working memory processing (see also McEvoy, Smith, & Gevins, 1998). For both domains, initial encoding was associated with a larger posterior than frontal P3, irrespective of

whether one or three items needed to be remembered. For the subsequent storage/maintenance of this information in working memory, remembering three items required more frontal than posterior resources than remembering a single item. Laterality effects were found as working memory load increased (i.e., remembering three items versus one) with the presence of larger left-frontal activity and reduced right-posterior activity.

Watter, Heisz, Karle, Shedden, and Kiss (2010) found a similar pattern of results during the study phase in a running working memory task by examining a posterior P3 component for remembering either verbal (number identity) or spatial (number location) items. For both domains, the amplitude of the P3 component varied by the amount of effortful control needed in memory, whereby a greater P3 was shown for updating versus maintenance versus a control condition with no memory component. However, the verbal task did elicit overall larger P3 mean amplitude than the spatial task for the two memory conditions. In addition, negative slow wave activity contained within a later 600 to 900 ms time window and situated above the dorsolateral prefrontal cortex was also analyzed. During this later time window, effects of laterality were present for the update condition. The left hemisphere was more sensitive to serial position effects for verbal than spatial working memory, whereas stronger serial position effects were present for right hemisphere spatial than verbal working memory. In summary, the posterior parietal P3 ERP component appears to be indexing levels of effortful control in memory that is utilized in a similar manner across stimulus domains and is the focus of Chapter 3.

Aging and Brain Functional Reorganization

With aging, working memory processing becomes compromised due to its dependence on effortful processing, and older adults show marked declines in performance compared to younger adults. The leading behavioural theories as to why older adults experience cognitive decline

involve slower speed of processing, problems with inhibitory control, limited cognitive resources, and problems with controlled as opposed to automatic processing (for review see Luo & Craik, 2008; Park & Festini, 2017). In a lifespan study of verbal and spatial N-back memory performance, spatial and more effortful 2-back memory tasks showed greater age-related decline than verbal and 1-back memory tasks, indicating the relevance of both domain and processing demands for older adult working memory performance (Cansino et al., 2013). At the neural level, substantial brain functional reorganization is associated with aging. In a review of PET and fMRI studies examining aging, working memory, episodic memory, encoding, and retrieval, Rajah and D'Esposito (2005) indicated that within specific divisions of the prefrontal cortex there are both age-related increases and decreases in activity. For instance, in the ventral prefrontal cortex, older adults typically show lower activation than younger adults during encoding, but then show a pattern of over-activation for retrieval. In the dorsal and anterior prefrontal cortex, older adults tended to show left-hemisphere over-activation and right-hemisphere under-activation, relative to younger adults, across studies.

For domain, rather than showing a left-lateralized pattern for verbal stimuli and a right-lateralized pattern for spatial stimuli that is common in younger adults, older adults instead recruited bilateral regions in the frontal lobes across tasks. In addition, within the dorsolateral prefrontal cortex, older adults showed opposing laterality effects to younger adults for verbal and spatial stimuli (Reuter-Lorenz et al., 2000). The Hemispheric Asymmetry Reduction in Older Adults (HAROLD, Cabeza, 2002) model describes this pattern of increased bilateral frontal activity that accompanies aging. It is still a matter of debate as to whether these broad network changes represent the process of dedifferentiation or neural function becoming less specific, or a method to compensate for cognitive decline (Grady, 2012).

There are two other influential theories of age-related brain functional reorganization. The posterior-anterior shift in aging (PASA) model indicates that with aging, there is increased frontal activity along with reduced posterior activity. Based on the relationship to performance, PASA is interpreted as a compensatory mechanism (Davis, Dennis, Daselaar, Fleck, & Cabeza, 2008). As will be discussed in Chapter 4, the directional change of PASA is opposite to what is seen with bilingualism (Grant, Dennis, & Li, 2014; Grundy, Anderson, & Bialystok, 2017a). Finally, the compensation-related utilization of neural circuits hypothesis (CRUNCH, Reuter-Lorenz, & Cappell, 2008) relates functional patterns in older adults to task difficulty and performance. When cognitive demands are low, older adults show higher activation than younger adults to uphold performance, but if the task requires more effortful control and negatively impacts performance, then the pattern reverses and older adults show lower activation than younger adults. These models of brain functional reorganization in aging will be considered in relation to bilingualism in the current dissertation.

A Proposed Model of Bilingual Working Memory

Currently, there is no comprehensive model of working memory that incorporates bilingualism as a factor. In their review of bilingual memory, Bartolotti and Marian (2012) point out that whether memories are stored in language-specific or language-nonspecific fashion can influence how memories are later accessed. Work with bilingual autobiographical memory retrieval appears to show language-specific effects whereby better retrieval is seen when the language at encoding matches that at retrieval (Marian & Neisser, 2000; Schrauf, 2000; Schrauf & Rubin, 1998; Schrauf & Rubin, 2000). The results from the bilingual autobiographical memory literature are in line with Tulving and Thompson's (1973) encoding specificity principle and Weingartner's (1978) state-dependent learning (Schrauf, 2000). Semantic memory or

memory tasks that rely more on conceptual processing show language-nonspecific effects (Durgunoğlu & Roediger, 1987), a finding that Bartolotti and Marian (2012) attribute to bilinguals' access to both languages. In addition, bilinguals show common areas of activation along with language-specific activation for memory for words in their known languages (Halsband, Krause, Sipilä, Teräs, & Laihinen, 2002; Xue, Dong, Jin, & Chen, 2004). In a model of bilingual versus monolingual working memory, performance will depend on ability for controlled processing and access to target representations. Figure 2 depicts a proposed model of bilingual working memory that takes these factors into account, called the Attentional Control and Retrieval Access (ACRA) account. As will be discussed in Chapter 2, bilinguals have difficulties with lexical retrieval (Gollan, Montoya, Cera, & Sandoval, 2008; Sullivan, Poarch, & Bialystok, 2017; Bialystok, Craik, & Luk, 2008a; 2008b), and thus, slower and less accurate access to verbal representations than monolinguals. On the other hand, as aforementioned, bilinguals should have an adapted attentional control system from consistently managing two active languages. Therefore, predictions for bilingual working memory performance can be made based on this account, whereby performance will be greater than monolinguals when the verbal demands are low, increasing access to target representations in working memory, and the attentional control demands are high. Better performance for monolinguals than bilinguals is expected when the verbal demands are high, decreasing access to target representations in working memory for bilinguals, and the attentional control demands are low. Other factors that reduce attentional control or access to representations, for instance aging, will negatively impact performance. Greater knowledge and use of target representations, for example, if an individual has a high English vocabulary score, should result in improved performance for bilinguals on verbal tasks due to increased ease of retrieval.

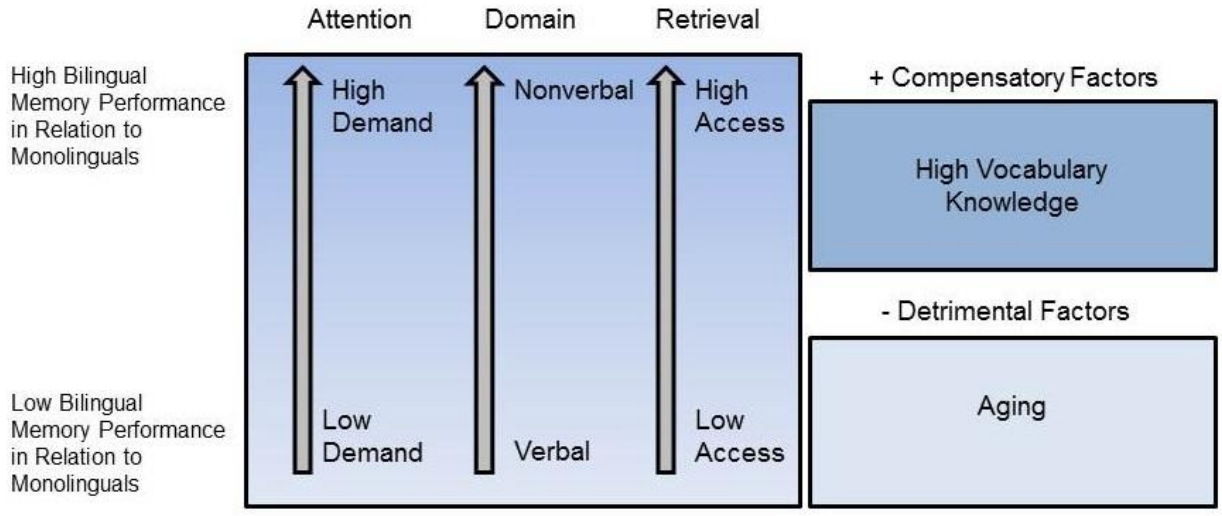


Figure 2. A proposed model of bilingual working memory, the Attentional Control and Retrieval Access (ACRA) account.

The Current Dissertation

As the ACRA model illustrates, two overarching themes encompass the three studies in the current dissertation examining working memory processing in younger and older adult bilinguals and monolinguals: the level of attention required and the verbal or nonverbal nature, or domain of the working memory task. Chapter 2 addresses these themes using a behavioural approach. Younger and older bilinguals and monolinguals performed three tasks that varied in their working memory demands. The star counting task is a verbal production task that required switching along with updating of counting rules in working memory. A nonverbal, modified flanker task that required rapid conflict monitoring and memory for response direction was included. The final paradigm was a nonverbal recent probe memory task that assessed proactive interference in working memory. In Chapter 3, the two themes are addressed in terms of both the study phase and probe recognition processing in working memory at the neural level. Younger

and older bilinguals and monolinguals performed a verbal and nonverbal version of a running working memory paradigm (Watter et al., 2010). The level of attention was manipulated by the task instructions, and the conditions consisted of a control condition assessing a simple perceptual decision, a maintenance memory condition, and a more effortful updating memory condition. Working memory was based on either digit identity (verbal) or location (spatial). ERPs were recorded during the study phase and at probe recognition to more precisely assess where age and language differences are occurring in the stream of working memory processing. In Chapter 4, the neural data from recognition from Chapter 3 were analyzed in terms of whole brain network patterns and signal variability, in the form of multiscale entropy, across groups and conditions (i.e., level of attention and domain). These novel analysis approaches provide greater detail on the intricacies of bilingual memory. Finally, in Chapter 5 the proposed behavioural ACRA model (see Figure 2) of bilingual memory and a proposed neural mechanism of bilingual memory across the lifespan are discussed in terms of the data gathered across all three investigations. The current dissertation is not an investigation of language group differences in working memory capacity, as shown with studies that use span tasks to see how many items individuals can hold in working memory, but will examine how working memory processing changes in relation to varying cognitive demands and target representations. This information will further general understanding of bilingual memory and provide some insight into uncovering the mechanism of cognitive reserve in aging that is associated with a lifetime experience of being bilingual.

Chapter 2. Executive Control Processes in Verbal and Nonverbal Working Memory

This chapter is a slightly edited version of the published manuscripts from the journal, *Linguistic Approaches to Bilingualism* (Sullivan, Prescott, Goldberg, & Bialystok, 2016) and the edited book, *Growing Old with Two Languages: Effects of Bilingualism on Cognitive Aging* (Sullivan, Prescott, Goldberg, & Bialystok, 2017).

The importance of attention in working memory is clear when one considers the cognitive operations needed to successfully encode, avoid irrelevant information/interference, maintain as well as retrieve information (Eriksson, Vogel, Lansner, Bergström, & Nyberg, 2015). This becomes relevant for how bilingualism impacts working memory performance as there is much evidence for the parallel activation of bilinguals' two languages (for a recent review see Kroll, Dussias, Bogulski, & Valdes-Kroff, 2012), and it has been put forth that bilinguals attend to both languages and therefore require the use of executive control to avoid interference (Bialystok, 2015). However, in contrast to a substantial amount of research showing that bilinguals outperform monolinguals on many nonverbal executive control tasks, with the largest effects seen in older adults and children (Bialystok, Craik, Green, & Gollan, 2009), studies examining the effect of bilingualism on working memory have produced more varied results (e.g., Bialystok, Craik, & Luk, 2008a; Luo, Craik, Moreno, & Bialystok, 2013). The purpose of the present study was to investigate the effect of bilingualism on working memory by considering the level of executive control required, presence or absence of interference, and verbal demands on the working memory task and the possible differences in these effects that might be found for younger and older adults. As Adesope, Lavin, Thompson, and Ungerleider (2010) point out, dual language activation in bilinguals could either increase cognitive load, making working memory processing more cumbersome (cf., van Merrienboer & Sweller, 2005) or the intense practice with attentional control that is required for bilingual language production may benefit working memory processing through practice (Luo, Craik, Moreno, & Bialystok, 2013). In both cases, these outcomes implicate the broader notion of executive control of which working memory is a component. Continual and lifelong experience with dual language control and, crucially, managing interference between languages suggests that better working memory

performance by bilinguals should be linked to the need for executive control (Kroll et al., 2012); however such an effect may have been obscured in previous work due to either low level executive control requirements of the task and/or the impact of verbal processing in the tasks due to the type of materials used.

Verbal memory performance in bilinguals is often confounded with language proficiency because receptive vocabulary is generally lower in both bilingual children (Bialystok, Luk, Peets, & Yang, 2010) and adults (Bialystok & Luk, 2012) than it is for their monolingual peers. Bilinguals across the lifespan also show reduced lexical access and slower retrieval in production tasks, including more tip of the tongue states (Gollan & Silverberg, 2001), slower picture naming in the first-language (L1) especially for low-frequency words (Gollan, Montoya, Cera, & Sandoval, 2008; Ivanova & Costa, 2008), and reduced verbal fluency, all of which impact tests of free recall. For instance, in a study by Fernandes, Craik, Bialystok, and Kreuger (2007), older and younger adult bilinguals and monolinguals performed a free recall test of semantically-related word lists under normal or divided attention conditions. Both bilinguals and older adults recalled fewer words, but the proportion of attention decrement in the divided attention conditions compared to the full attention condition was equivalent to monolinguals and younger adults. These findings suggest that both older adults and bilinguals were not further hindered by interference effects, despite recalling fewer words. Importantly, the effect of bilingualism but not aging disappeared after controlling for vocabulary and nonverbal fluid intelligence, indicating that although both older adults and bilinguals have initial difficulty with lexical retrieval, only age-related detriments on verbal recall remain once language proficiency is accounted for. Further analyses revealed that poorer bilingual performance was tied to the full attention condition and only one of the four divided attention conditions, a pattern that the authors

interpreted as utilization of a more efficient executive control system to improve performance on the effortful conditions making it comparable to that of monolinguals.

In another study with young adults, a similar influence of verbal ability on verbal memory and interference was shown by having bilinguals and monolinguals recall four sequential word lists, with the first three lists containing words from the same semantic category to accumulate proactive interference (i.e., interference from previously relevant material, see Jonides & Nee, 2006) and the fourth list containing words from a separate semantic category to erase proactive interference. There were no language group differences in verbal recall or number of intrusions, but when differences in vocabulary knowledge were controlled, the bilinguals showed better verbal recall than monolinguals (Bialystok & Feng, 2009). The essential point from both of these studies is that bilinguals perform equivalently to or even better than monolinguals after verbal ability is considered, and importantly better working memory performance is seen in bilinguals for the conditions involving controlled processing and interference.

To avoid the potential confound of language proficiency on working memory performance, Bialystok, Craik, and Luk (2008a) asked younger and older bilingual and monolingual adults to perform nonverbal span tasks -- forward and backward Corsi blocks and a self-ordered pointing task. Younger bilinguals recalled more than younger monolinguals on the Corsi blocks task, but there were no language group differences in older adults. On the self-ordered pointing task, there were age-related differences in performance but no effect of language group. The lack of language group differences seen with aging for these two tasks may be because they are simple span tasks with little need for executive control. The suggestion is that bilinguals outperform monolinguals only on tasks that make substantial demands on

executive control, and the implication is that working memory tasks that depend on executive control are more likely to show better performance by bilinguals than by monolinguals. An example of this comes from the Simon task (Lu & Proctor, 1995) that was adapted to create a working memory manipulation (Bialystok, Craik, Klein, & Viswanathan, 2004). The task included conditions in which participants responded to the colour of either two stimulus options (blue or brown) or four stimulus options (pink, yellow, red, or green) that were placed on the left or right side of the screen in compatible or incompatible positions with the correct response key. Independent of differences in the Simon effect, both younger and older bilinguals outperformed their monolingual counterparts in the more demanding 4-colour conditions. Therefore, bilinguals appear to show better working memory performance on tasks involving nonverbal, speeded responses that require the use of executive control.

The interaction between domain-specific ability and domain-general executive control on memory performance can be shown by testing monolinguals and bilinguals on the same task using different stimuli. Luo, Craik, Moreno, and Bialystok (2013) gave younger and older bilinguals and monolinguals simple and complex verbal and spatial span tasks. An interaction between language group and domain showed that monolinguals were better than bilinguals on verbal tasks and bilinguals were better than monolinguals on spatial tasks, differences that were stable across age groups. These effects remained after controlling for vocabulary and nonverbal intelligence. Although these data are in line with the current predictions, language differences are not always seen for span tasks (e.g. Bialystok, Craik, & Luk, 2008a), suggesting that the executive control requirements in these tasks may not be sufficient to elicit such differences.

Two additional studies have used the same task across different domains with older and younger adult bilinguals but have focused more on isolating controlled processing components in

memory performance. First, Wodniecka, Craik, Luo, and Bialystok (2010) used a process dissociation paradigm (PDP; Jacoby, 1991) that was designed to assess the effects of aging and bilingualism on measures of familiarity and recollection. Familiarity is an automatic process but recollection requires controlled processing, or executive control. The typical age-related declines were found for recollection, but language group effects depended on both domain and pre-existing ability. Older adult bilinguals for whom English was a second-language (L2) displayed poorer performance for verbal recollection but better performance for nonverbal recollection than older adult monolinguals. In contrast, bilinguals with stronger English proficiency showed the reverse effect in which older adult bilinguals displayed better performance than older adult monolinguals in verbal recollection. Bilinguals of both age groups outperformed monolinguals for nonverbal recollection. These studies provide some evidence for better bilingual performance in the controlled processes of recollection but not automatic familiarity, with clearer differences for older adult bilinguals and nonverbal tasks.

Finally, evidence that language group differences in nonverbal memory may be tied to the need to resolve interference comes from the recent probe task (Jonides & Nee, 2006). Participants must make yes/no decisions to a single probe as to whether it appeared in the previous memory set slide. The key manipulations are trials designed to elicit facilitation, i.e., the probe was present in the memory set and trial n-1, or interference effects, i.e., the probe was not present in the memory set but was present for trial n-1. This proactive interference condition was of interest for the current study for two reasons. First, it is well documented that older adults are more susceptible to proactive interference effects than younger adults (e.g., Jonides, Marshuetz, Smith, Reuter-Lorenz, Koeppe, & Hartley, 2000; May, Hasher, & Kane, 1999). Second, the presence of proactive interference introduces a situation in which previous

information that is highly familiar creates a response bias to respond ‘yes’ when in reality, a negative response is required (Jonides et al., 2000), creating the need for conflict resolution. This presents a scenario in working memory that is similar to the nature of the bilingual experience where conflict resolution/attention is required to deal with the interference from two separate languages. With respect to the PDP previously described, the probe in the interference condition elicits a sense of familiarity in memory, however recollection/controlled processing is required to establish the appropriate contextual details as to whether the probe was indeed in the current memory set (see Wodniecka et al., 2010). In a study by Bialystok, Poarch, Luo, and Craik (2014), younger and older bilingual and monolingual adults performed a letter version and a nonverbal stick figure version of the recent probe task. Younger adults performed better than older adults for both versions, but there were no effects of language group for the letter task. The key findings were that for the nonverbal figure task, bilinguals were faster than monolinguals on negative interference trials and showed smaller costs with greatest effects in older adults.

The current study was designed to determine the conditions under which bilingual processing differences could be found in working memory tasks. The hypothesis was that better bilingual performance is tied to the need for executive control in performing the task, with the largest executive control demands recruited by interference. Older and younger adult participants of monolingual or bilingual language backgrounds were included to assess whether bilingualism would also act as a protective factor against typical age-related declines in memory performance. Domain-specific effects were assessed by including verbal and nonverbal materials.

In the verbal domain, participants performed a star counting task. The executive control demands consisted of manipulating the required number of switches from forward to backward counting of stars that were presented in rows on a card. Working memory demands were

increased in a condition in which a more effortful counting rule had to be remembered, namely, count forward by 2s and backward by 1s in contrast to the standard condition in which all counting was by 1s. The star counting task was developed to assess attention regulation and shows a stronger correlation with the processing aspects of numerical span than storage (Das-Smaal, de Jong, & Koopmans, 1993). Bilingual participants were allowed to use their preferred language of counting to limit possible slowing due to lexical retrieval.

In the nonverbal domain, a flanker task was developed that required responses to the correct or opposite central arrow direction depending on the colour. This manipulation added working memory demands to a well-established executive control task, as opposed to the other two tasks (i.e., star counting and recent probe) where executive control conditions were present within primarily working memory tasks. Finally, a complex nonverbal recent probe memory task was included that contained a proactive interference manipulation and used different nonverbal stimuli from Bialystok et al. (2014). The first hypothesis was that complex task conditions that require more executive control, particularly interference resolution, will be performed better by younger participants and bilinguals, with larger language group effects in older adults based on the findings of Bialystok et al. (2014). The second hypothesis was that performance will depend on whether the task is verbal or nonverbal. Better performance by bilinguals should be tied to nonverbal tasks, and once vocabulary knowledge is controlled for, bilinguals' ability to handle executive control requirements in the verbal task should outweigh problems due to lexical retrieval.

Method

Participants

There were 115 participants, consisting of older and younger adults with monolingual or

bilingual language backgrounds. Thirteen participants were excluded for having unclear language backgrounds (n = 6), low English vocabulary or nonverbal intelligence (standardized scores < 70; n = 3), history of a lobotomy/cerebral palsy (n = 1), full vision in only one eye (n =1), less than high school education (n = 1), and one older monolingual for having very low performance across all three experimental tasks (star counting accuracy = 6.3%, modified flanker accuracy = 33%, recent probe accuracy = 53%). The final younger adult sample included 53 participants between the ages of 18 and 38 (M = 21.1, SD = 4.1), of whom 26 were monolingual English speakers and 27 were bilinguals who reported being fluent in English and at least one other language[1]. The final older adult sample consisted of 49 participants between the ages of 63 and 80 (M = 71.0, SD = 4.9), of whom 23 were English monolinguals and 26 were bilinguals[2].

Background Measures

Participants completed the Language and Social Background Questionnaire (LSBQ; Anderson, Mak, Keyvani Chahi, & Bialystok, 2018; Luk & Bialystok, 2013) to obtain information about language experience. Participants answered questions about their language use and proficiency for all known languages and rated their level of bilingualism on a global self-assessment scale. Additionally, they answered questions regarding age, gender, handedness, vision/hearing problems, neurological impairments, psychoactive medication use, education level, and country of birth. Older adults also reported their occupation, and younger adults answered questions about their parents' education levels, occupations, and known languages.

Vocabulary and nonverbal fluid intelligence were assessed by the paper-based versions of

[1] The non-English languages of the younger adult bilinguals included Cantonese (3), Portuguese (1), Ilocano (2), Armenian (1), Bisaya (1), French (3), Hindi (2), Farsi (1), Vietnamese (1), Ukrainian (1), Punjabi (1), Bangla (1), Amharic (1), Spanish (2), Korean (1), Albanian (1), Urdu (2), Pashto (1), and Creole (1).

[2] The non-English languages of the older adult bilinguals included Bengali (1), French (4), Spanish (1), Yiddish (3), Swiss German (1), Turkish (1), Filipino (2), Estonian (1), Marathi (1), Russian (1), Dutch (1), German (2), Mandarin Chinese (Fookien Dialect) (1), Hindi (1), Tamil (1), Italian (1), Hebrew (1), Ukrainian (1), and Urdu (1).

the Shipley-2 Institute of Living Scale- Vocabulary and Block Patterns Scales (Shipley, Gruber, Martin, & Klein, 2009). Responses were scored and standardized according to the published instructions. Each test has a population mean of 100 and a standard deviation of 15.

Tasks

Paper-and-pencil and computer-based tasks were used to assess verbal (star counting) and nonverbal (flanker, recent probe) working memory.

Star counting task. The star counting task required participants to follow specific rules and count out loud the number of stars that appeared on a page (adapted from Das-Smaal, de Jong, & Koopmans, 1993). Laminated 8 ½ x 11 inch sheets with arrangements of black stars and interspersed plus and minus signs at unpredictable locations were presented. The signs indicated the counting direction, with plus signalling count forward and minus signalling count backward. Each sheet had a number in the upper left corner beside the first row of stars indicating the number from which counting was to begin. Participants were to move across the rows from left to right, and to proceed down the rows from the top to bottom of the card. In the standard condition, both forward and backward counting proceeded by intervals of one; in the working memory condition, forward counting proceeded by twos but backward counting by ones. This counting rule (2 Forward, 1 Backward) was printed in red on the left side of each card in the working memory condition (see Appendix A for a sample card). Both the standard and working memory conditions were further divided into low switch and high switch conditions. Each low switch card had four signs indicating a change in counting direction, and each high switch card contained ten signs. There were sixteen cards, with four in each of the four conditions. The order of conditions and the order of cards within each condition were randomized across participants.

Modified flanker task. To increase working memory demands in a simple executive

control task, a modified flanker task was developed. Stimuli were presented in the center of the screen with a response key on either side of the screen. Each trial began with a central fixation cross for 250 ms, followed by a response screen (see Appendix B). Trials timed out after 2000 ms. For baseline trials, a single blue or pink arrow appeared and participants indicated the direction it was pointing if the arrow was blue (same condition) but the opposite direction if it was pink (opposite condition). Conflict block trials consisted of five arrows presented in a horizontal line across the center of the screen consisting of two flanking black arrows on either side of a central blue or pink arrow. The flanking arrows pointed in the same direction as the center arrow for congruent trials, but in the opposite direction for incongruent trials. For both congruent and incongruent trials, central blue and pink arrows indicated same and opposite conditions respectively. Participants completed two blocks of each trial type (single and conflict) in alternating order. There were 48 single arrow trials, consisting of 24 same trials and 24 opposite trials, and 96 conflict block trials, consisting of 48 congruent trials (24 same and 24 opposite) and 48 incongruent trials (24 same and 24 opposite). Colours assigned for the same and opposite trials were counterbalanced across participants.

Recent probe task. This task examines the effect of proactive interference on the ability to perform a simple memory task. The stimuli were 26 Microsoft Word Wingdings symbols (e.g., ♈, ♉, ⌘). Trials began with a central fixation cross presented for 1000 ms, followed by a memory set for 2500 ms (see Appendix C). The memory set then disappeared and the fixation cross remained on the screen for 1500 ms until the probe appeared. The probe slide timed out after 3000 ms. Each memory set contained four symbols arranged in a square surrounding the fixation cross. Probe screens contained a single symbol in the center of the screen. There were four trial types created by two factors. The first was whether the probe appeared in the memory

set, creating positive (‘yes’) and negative (‘no’) trials. Second, the probe may also have appeared in the previous (n-1) set, creating facilitation for positive trials but interference for negative trials. Positive and negative baseline trials were those in which the probe did not appear in the previous memory set. The task consisted of a pure block of 32 trials (16 positive baseline and 16 negative baseline), two mixed blocks with 64 trials each (16 of each of the four trial types), and another pure block of 32 trials (16 positive baseline and 16 negative baseline). The task was programmed using a pseudorandomized order, such that no more than three of the same trial type would be presented in sequence.

Procedure

Participants completed all tasks in a single 2-hour session. Upon arrival, participants completed the consent form and the LSBQ. The experimenter then administered the Shipley-2 Vocabulary and Shipley-2 Block Patterns Scales according to standardized instructions.

For the star counting task, the experimenter sat at a table across from the participant and presented each card on the table individually. Bilingual participants were told they were allowed to count in their preferred language. A practice card was presented before the first experimental card to familiarize participants with the counting rules. For each card, the experimenter recorded the participant’s final time in seconds and answer.

The modified flanker and recent probe tasks were completed on a Dell Dimension 8400 desktop using E-Prime (Version 2.0, Psychology Software Tools) software. The order of the two tasks was counterbalanced across participants. For the modified flanker task, the ‘Q’ key on the left side of the keyboard was used as the left response key and the ‘P’ key on the right side of the keyboard was the right response key. Participants were instructed to press the button on the same side as the arrow was pointing to for blue arrows (same) and on the opposite side for pink arrows

(opposite). Participants completed eight practice trials with feedback before each block, and were told to respond as quickly as possible while avoiding errors. For the recent probe task, participants completed eight practice trials with verbal feedback, and were told to respond as quickly as possible while avoiding errors. The response designation ('yes' or 'no') for each response key ('Q' or 'P') was specified in the instructions given before the task and was counterbalanced across participants.

Results

Background Measures

Background measures are reported in Table 1 by age group and language group. Two-way ANOVAs for age group and language group were run on the variables age in years, years of education, English vocabulary scores, and nonverbal intelligence scores. For age in years, there was an expected main effect of age group, $F(1, 98) = 3163.31$, $p < .0001$, $\eta^2_p = .97$, but importantly, no main effect or interactions with language group, Fs < 1.5. For years of education, there was a main effect of age group, $F(1, 98) = 51.23$, $p < .0001$, $\eta^2_p = .34$, with older adults having more years of education than younger adults, but no main effect or interactions with language group, Fs < 2.3. English vocabulary scores were significantly higher in older adults than younger adults, $F(1, 98) = 31.43$, $p < .0001$, $\eta^2_p = .24$, and higher in monolinguals than in bilinguals, $F(1, 98) = 9.36$, $p = .003$, $\eta^2_p = .09$, with no significant interaction, $F < 1$. There were no significant main effects or interactions for nonverbal intelligence scores, Fs < 3.9. Language profiles are shown in Table 2.

Table 1

Means (and SDs) of Background Variables by Age Group and Language Group

Age	Younger Adults		Older Adults	
Group	Monolinguals	Bilinguals	Monolinguals	Bilinguals
N	26	27	23	26
Sex	14 F, 12 M	21 F, 6 M	16 F, 7 M	17 F, 9 M
Handedness	20 R, 5 L, 1 A	26 R, 1 L	21 R, 2 L	25 R, 1 A
Age (years)	21.2 (4.3)	21.0 (4.0)	70.0 (4.4)	71.9 (5.1)
Education (years)	13.0 (1.1)	13.3 (1.5)	15.1 (1.8)	15.8 (2.1)
Vocabulary	101.5 (7.9)	95.1 (11.3)	111.2 (6.8)	106.3 (10.3)
Nonverbal Intelligence	100.7 (9.6)	97.6 (13.9)	101.7 (14.1)	95.3 (10.7)

Note. Vocabulary and nonverbal intelligence were measured using the Shipley-2 Vocabulary and Shipley-2 Block Patterns Scales respectively, which are standardized by age group. Sex: F – Female, M – Male. Handedness: R – Right, L – Left, A – Ambidextrous.

Table 2

Language Profile Means (and SDs) by Language Group and Age Group

	Bilingual		Monolingual	
	Younger	Older	Younger	Older
Age Learned English	6.2 (5.3)	8.8 (6.0)	1.1 (1.2)	0.9 (0.9)
Age Learned Non-English Language	2.0 (3.0)	1.9 (3.7)	8.1 (5.3) n = 11	11.6 (5.5) n = 7
N Indicated English as L1[a]	13/27	15/26	26/26	23/23
English Proficiency	91.6 (10.2)	97.3 (4.4)	99.9 (0.5)	99.2 (2.5)

Non-English Proficiency	91.9 (10.2)	90.7 (12.5)	8.0 (12.0)	6.0 (10.6)
English Usage	60.4 (19.8)	70.8 (22.8)	98.6 (4.2)	99.3 (2.2)

[a]*L1*. Language listed first when asked to list known languages in order of fluency.

Note. Self-report ratings of proficiency range from 0 = "no proficiency" and 100 = "fully fluent" and usage from 0 = "All L2" and 100 = "All English".

Star Counting Task

Mean counting time and accuracy rates for the star counting task are presented in Table 3. RT analyses were conducted on correct trials. Any trials noted by the experimenter where participants restarted counting, made a counting infringement (i.e., did not count each individual star), made a substantially long pause to correct themselves[3], or stopped before completing the entire card were classified as errors. One younger bilingual did not perform the task. Initially, a four-way mixed ANOVA with age group and language group as the between-subjects variables, and switch condition (low or high) and counting rule (standard or working memory) as within-subjects variables was used to analyze the counting time data. A significant main effect of language group was found, $F(1, 91) = 5.43$, $p = .02$, $\eta^2_p = .06$, and bilinguals had slower counting times than monolinguals. A main effect of switch showed that participants were faster in low switch than high switch conditions, $F(1, 91) = 253.48$, $p < .0001$, $\eta^2_p = .74$, and a main effect of counting rule indicated that participants were faster in standard conditions than in working memory conditions, $F(1, 91) = 428.80$, $p < .0001$, $\eta^2_p = .82$. There was also a significant three-way interaction of switch by counting by age, $F(1, 91) = 4.29$, $p = .04$, $\eta^2_p = .05$. Separate univariate analyses by condition, revealed that this interaction was driven by older adults being

[3] This occurrence was noted by the experimenter for a single card for two older adult bilinguals; with the trial length containing the pause to be substantially longer than the mean of the remaining three cards of that condition (12.2 seconds longer for one participant and 26.8 seconds longer for the other participant).

significantly slower than younger adults on the low switch/standard counting condition (p = .01), but not the remaining conditions (Fs < 1). There were no other significant main effects or interactions, Fs < 3.5.

Because the groups were not equivalent in vocabulary and due to the verbal nature of the task, a correlational analysis was conducted to determine whether there was a relationship between vocabulary and counting times across the four conditions. There was a significant negative correlation for the full sample[4], and higher vocabulary scores were associated with faster production, $r(93) = -.31$, $p = .003$. A four-way mixed ANCOVA with vocabulary as a covariate was used to re-examine the data. Based on these adjusted scores, there was a significant main effect of age, $F(1, 90) = 5.73$, $p = .02$, $\eta^2_p = .06$, with slower counting time by older adults than younger adults, but not language group, $F < 1.9$, and no interaction, $F < 1$. Thus, the slower performance of bilinguals disappeared when vocabulary levels were taken into account. There was again a main effect of switch, $F(1, 90) = 14.76$, $p = .0002$, $\eta^2_p = .14$, and a main effect of counting rule, $F(1, 90) = 15.21$, $p = .0002$, $\eta^2_p = .14$. The three-way interaction of switch by counting by age remained significant, $F(1, 90) = 6.23$, $p = .01$, $\eta^2_p = .06$, however now older adults were significantly slower for both the low switch/standard condition (p = .0002) and the high switch/working memory condition (p = .03), but not the remaining two conditions (Fs < 3.5). There were no other significant interactions, Fs < 3.9.

Analyses of the star counting task accuracy data (see Table 3) using a four-way mixed ANOVA revealed significant task effects, with higher accuracy on low switch than high switch conditions, $F(1, 96) = 30.68$, $p < .0001$, $\eta^2_p = .24$ and on standard than working memory

[4] To justify use of the ANCOVA, the assumption of homogeneity of the regression slope was examined by also looking at the correlations between vocabulary and production time separately by age and language group. The assumption was met as similar slopes were shown across all four subgroups, with all correlations ranging between -.27 to -.42.

conditions, $F(1, 96) = 15.08$, $p = .0002$, $\eta^2_p = .14$. There were no other significant main effects or interactions, Fs < 1.8.

Table 3

Mean Counting Times in Seconds (and SDs), LS Means (and SDs) Using English Vocabulary as a Covariate, and Mean Accuracy (and SDs) for the Star Counting Task by Age Group and Language Group

	Younger Adults		Older Adults	
Condition	Monolinguals	Bilinguals	Monolinguals	Bilinguals
		Counting Time		
Standard				
Low Switch	28.5 (7.6)	31.3 (8.3)	31.4 (7.2)	36.6 (8.8)
High Switch	39.1 (9.9)	45.9 (12.9)	41.6 (9.5)	45.4 (11.3)
Working Memory				
Low Switch	44.0 (12.0)	49.7 (11.0)	43.8 (10.0)	51.2 (15.5)
High Switch	50.8 (13.5)	56.3 (15.8)	53.1 (13.7)	57.1 (15.4)
		LS Means		
Standard				
Low Switch	28.0 (7.7)	29.1 (8.3)	33.5 (8.2)	37.4 (7.7)
High Switch	38.6 (10.6)	43.0 (11.5)	44.3 (11.3)	46.4 (10.7)
Working Memory				
Low Switch	43.5 (12.0)	46.9 (13.1)	46.4 (12.8)	52.2 (12.1)
High Switch	50.0 (13.8)	51.8 (15.0)	57.3 (14.8)	58.6 (13.9)
		Accuracy[a]		
Standard				
Low Switch	3.4 (0.9)	3.3 (0.8)	3.5 (0.8)	3.5 (0.8)

High Switch	3.0 (1.0)	2.8 (0.9)	2.7 (1.1)	3.0 (0.9)
Working Memory				
Low Switch	3.0 (0.8)	2.8 (1.1)	3.0 (0.9)	3.0 (1.1)
High Switch	2.6 (1.1)	2.7 (1.1)	2.5 (0.8)	2.7 (1.1)

[a]Accuracy rates are based on the number of cards performed correctly out of 4.

Modified Flanker Task

Six participants (1 younger monolingual, 1 younger bilingual, and 4 older bilinguals) who had an overall accuracy rate below 60% (- 2.5 *SDs* from the full study sample mean) on this task were excluded from the analyses. One additional older monolingual did not complete the task. RT trimming procedures consisted of removing trials with RTs below 200 ms, eliminating 0.03% of trials for younger adults and 0.03% of trials for older adult participants. RT analyses were conducted on correct trials only.

Results for the flanker task are presented in Table 4. Reaction times for the single arrow condition were analyzed using a three-way mixed ANOVA using age, language group, and direction (same or opposite). There was a significant main effect of age, $F(1, 91) = 50.87$, $p < .0001$, $\eta^2_p = .36$, with younger adults responding faster than older adults, and a significant main effect of direction, $F(1, 91) = 16.25$, $p = .0001$, $\eta^2_p = .15$, with same trials faster than opposite trials. There were no other significant main effects or interactions, Fs < 2.8.

For conflict block reaction times, a four-way mixed ANOVA, with age, language group, congruency (congruent or incongruent) and direction (same or opposite) revealed a main effect of age, $F(1, 91) = 51.70$, $p < .0001$, $\eta^2_p = .36$, with faster responding by younger adults, and language group, $F(1, 91) = 4.96$, $p = .03$, $\eta^2_p = .05$, with faster responding by monolinguals. There was a main effect of congruency, $F(1, 91) = 6.08$, $p = .02$, $\eta^2_p = .06$, with the average response to congruent trials being faster than incongruent. There was also a main effect of

direction, $F(1, 91) = 47.72$, $p < .0001$, $\eta^2_p = .34$, with longer RTs for opposite trials, and a significant direction by age interaction, $F(1, 91) = 4.57$, $p = .04$, $\eta^2_p = .05$, with older adults showing substantially longer RTs to opposite direction trials than younger adults. There were no other significant interactions, all Fs < 3.3.

A conflict direction cost score was calculated to investigate the RT costs due to keeping the opposite direction responding rule in mind (working memory cost score). This was operationalized as ((congruent opposite + incongruent opposite)/2 – (congruent same + incongruent same)/2). For this cost score, there was a significant main effect of age group, $F(1, 91) = 4.57$, $p = .04$, $\eta^2_p = .05$, but not language group, $F < 1$, and no interaction, $F < 1$ (M_{YML} = 30.7, SD_{YML} = 58.5, M_{YBL} = 31.9, SD_{YBL} = 55.6, M_{OML} = 63.8, SD_{OML} = 67.7, M_{OBL} = 55.0, SD_{OBL} = 73.9).

Table 4

Mean RTs (and SDs) and Percent Accuracy (and SDs) for the Modified Flanker Task by Age Group and Language Group

	Younger Adults		Older Adults	
Condition	Monolinguals	Bilinguals	Monolinguals	Bilinguals
Single Arrow Blocks RT				
Same Direction	680 (145)	745 (156)	890 (132)	949 (151)
Opposite Direction	710 (151)	763 (157)	950 (154)	976 (177)
Conflict Blocks RT				
Congruent				
Same Direction	664 (137)	736 (118)	839 (118)	903 (149)
Opposite Direction	681 (118)	762 (160)	905 (132)	970 (181)

Incongruent				
Same Direction	664 (135)	725 (129)	867 (126)	927 (160)
Opposite Direction	709 (155)	762 (157)	929 (124)	970 (182)
Single Arrow Blocks Accuracy				
Same Direction	95.8 (4.7)	94.4 (8.7)	93.8 (6.9)	92.2 (9.9)
Opposite Direction	95.2 (6.3)	92.1 (11.6)	90.7 (10.0)	86.2 (18.4)
Conflict Blocks Accuracy				
Congruent				
Same Direction	95.7 (6.4)	92.6 (6.3)	94.3 (7.6)	93.4 (8.9)
Opposite Direction	96.5 (5.7)	92.6 (9.0)	92.4 (7.9)	92.1 (11.3)
Incongruent				
Same Direction	93.7 (7.2)	93.8 (6.9)	93.8 (7.5)	94.1 (6.4)
Opposite Direction	94.3 (6.1)	93.0 (8.6)	91.9 (9.3)	92.0 (7.9)

The analysis of single arrow accuracy demonstrated that younger adults were more accurate than older adults, $F(1, 91) = 4.10$, $p = .046$, $\eta^2_p = .04$. Accuracy was higher for same direction trials than opposite direction trials, $F(1, 91) = 7.82$, $p = .0063$, $\eta^2_p = .08$. There were no other significant main effects or interactions, Fs < 2.2. For conflict block accuracy, there was a significant interaction of congruency by language group, $F(1, 91) = 4.78$, $p = .031$, $\eta^2_p = .05$. A follow-up two-way ANOVA collapsing across age group and direction was run to explore this interaction. Tukey's multiple comparison tests indicated that the language groups did not differ for either level of congruency. Contrasts (αcorrection = (.05/2) = .025) were then performed to test for congruency effects within each language group. Monolinguals showed a significant effect of congruency, $F(1, 46) = 6.34$, $p = .015$, $\eta^2_p = .12$, with higher accuracy for congruent (*M*

= 94.8, *SD* = 6.3) than incongruent trials (*M* = 93.4, *SD* = 6.6). Bilinguals did not show an effect of congruency, $F < 1$, with similar accuracy shown for congruent (*M* = 92.7, *SD* = 7.2) and incongruent trials (*M* = 93.2, *SD* = 6.1). There were no other significant main effects or interactions from the initial four-way ANOVA on conflict block accuracy, *F*s < 1.8.

Recent Probe Task

Results from the recent probe task are reported in Table 5. Two younger bilingual participants were excluded because one had RTs greater than 3 *SDs* above the group mean for 3 of the 6 task conditions, and the other due to a technical error. Two further participants were removed because of an overall accuracy rate below 54% (1 younger bilingual, and 1 older bilingual; - 2.5 *SDs* from the full study sample mean). RT trimming procedures consisted of removing trials with RTs below 300 ms or above 2500 ms. This eliminated 0.7% of trials for younger adults and 1.2% of trials for older adults. All RT analyses were conducted on correct trials only.

For the pure blocks, a three-way mixed ANOVA for age, language group, and response type ('no' or 'yes') on RT revealed a main effect of age, $F(1, 94) = 53.53$, $p < .0001$, $\eta^2_p = .36$, with faster responding by younger adults. There were no other significant main effects or interactions, all *F*s < 3.2. Pure block accuracy analysis revealed a main effect of age, $F(1, 94) = 21.54$, $p < .0001$, $\eta^2_p = .19$, with higher accuracy for younger adults, but no effect of or interaction with language group, *Fs* < 2. There was also an effect of response type, $F(1, 94) = 39.07$, $p < .0001$, $\eta^2_p = .29$, with higher accuracy for negative responses. There were no significant interactions, all *F*s < 2.4.

Mixed block trials for RT were analyzed using a four-way mixed ANOVA for age, language group, response type, and trial type (baseline or interference/facilitation) and revealed a

main effect of age, $F(1, 94) = 42.65$, $p < .0001$, $\eta^2_p = .31$, with faster responding by younger adults. There was a main effect of trial type, $F(1, 94) = 26.59$, $p < .0001$, $\eta^2_p = .22$, with faster responding on baseline than experimental (facilitation/interference) trials. There was also a response by trial interaction, $F(1, 94) = 33.23$, $p < .0001$, $\eta^2_p = .26$, in which participants overall responded similarly to facilitation trials ($M = 1047$, $SD = 226$) and positive baseline trials ($M = 1048$, $SD = 241$), but were slower to interference trials ($M = 1112$, $SD = 239$) than negative baseline trials ($M = 1039$, $SD = 227$), indicating that only interference affected RT. Importantly, there was also a significant three-way interaction of response by trial by language, $F(1, 94) = 4.03$, $p = .0475$, $\eta^2_p = .04$. Univariate analyses by condition indicated that bilinguals were faster on interference trials ($p = .04$), but not on the other three types (Fs < 2.9). No other interactions were significant, Fs < 3.9.

An analysis of mixed block accuracy showed a significant effect of age, $F(1, 94) = 12.81$, $p = .0005$, $\eta^2_p = .12$, such that younger adults were more accurate than older adults. There was a significant effect of response type, $F(1, 94) = 25.77$, $p < .0001$, $\eta^2_p = .22$, with higher accuracy for negative responses, as well as a significant response by trial interaction, $F(1, 94) = 38.56$, $p < .0001$, $\eta^2_p = .29$. This interaction represents the expected experimental manipulation, with overall higher accuracy for facilitation ($M = 77.4$, $SD = 13.7$) than positive baseline trials ($M = 73.9$, $SD = 15.6$), and lower accuracy for interference ($M = 81.7$, $SD = 11.6$) than negative baseline trials ($M = 87.2$, $SD = 10.3$). There were no other significant main effects or interactions, all Fs < 3.7.

Table 5

Mean RTs (and SDs) and Percent Accuracy (and SDs) for the Recent Probe Task by Age Group and Language Group

	Younger Adults		Older Adults	
Condition	Monolinguals	Bilinguals	Monolinguals	Bilinguals
Pure blocks		RT		
Negative baseline	971 (159)	873 (141)	1192 (181)	1153 (209)
Positive baseline	986 (196)	904 (132)	1192 (218)	1173 (195)
Mixed blocks				
Negative baseline	969 (199)	880 (127)	1164 (197)	1150 (240)
Interference	1069 (199)	932 (141)	1244 (226)	1210 (249)
Positive baseline	963 (171)	871 (141)	1206 (265)	1160 (213)
Facilitation	967 (204)	897 (132)	1184 (234)	1149 (195)
Pure blocks		Accuracy		
Negative baseline	87.6 (8.2)	91.0 (7.8)	84.9 (12.2)	82.5 (13.3)
Positive baseline	81.7 (11.0)	78.5 (13.9)	73.4 (13.1)	66.4 (17.2)
Mixed blocks				
Negative baseline	87.5 (10.8)	88.5 (8.6)	87.9 (9.1)	84.9 (12.2)
Interference	82.6 (12.5)	84.8 (9.1)	79.9 (11.4)	79.4 (12.9)
Positive baseline	81.7 (10.9)	72.8 (15.9)	73.2 (16.7)	67.3 (15.8)
Facilitation	83.9 (7.6)	79.7 (11.8)	74.6 (16.7)	71.1 (14.4)

The same data were analyzed as RT cost scores that were calculated following the

procedures in Bialystok et al. (2014). Facilitation effects were represented as mixed block positive baseline - facilitation trials, and interference effects were represented as mixed block negative baseline - interference trials. These data are presented in Figure 3. A three-way mixed ANOVA with age group, language group, and experimental trial type (facilitation effect, interference effect) was run on these cost scores. One younger bilingual outlier was removed for having a large negative cost score close to 3 *SDs* minus the group mean. There was a significant main effect of trial type, $F(1, 93) = 31.53$, $p < .0001$, $\eta^2_p = .25$, indicating again the presence of a large cost on RTs from interference ($M = -70.7$, $SD = 92.6$) and no effect of facilitation ($M = 0.8$, $SD = 93.0$). There was a significant trial by language interaction, $F(1, 93) = 5.05$, $p = .027$, $\eta^2_p = .05$. One-way ANOVAs examining the effect of language on each experimental trial type indicated that bilinguals had smaller interference costs than monolinguals ($p = .03$), but the groups did not differ on facilitation ($F < 1$). There were no other significant main effects or interactions, all Fs < 1.5.

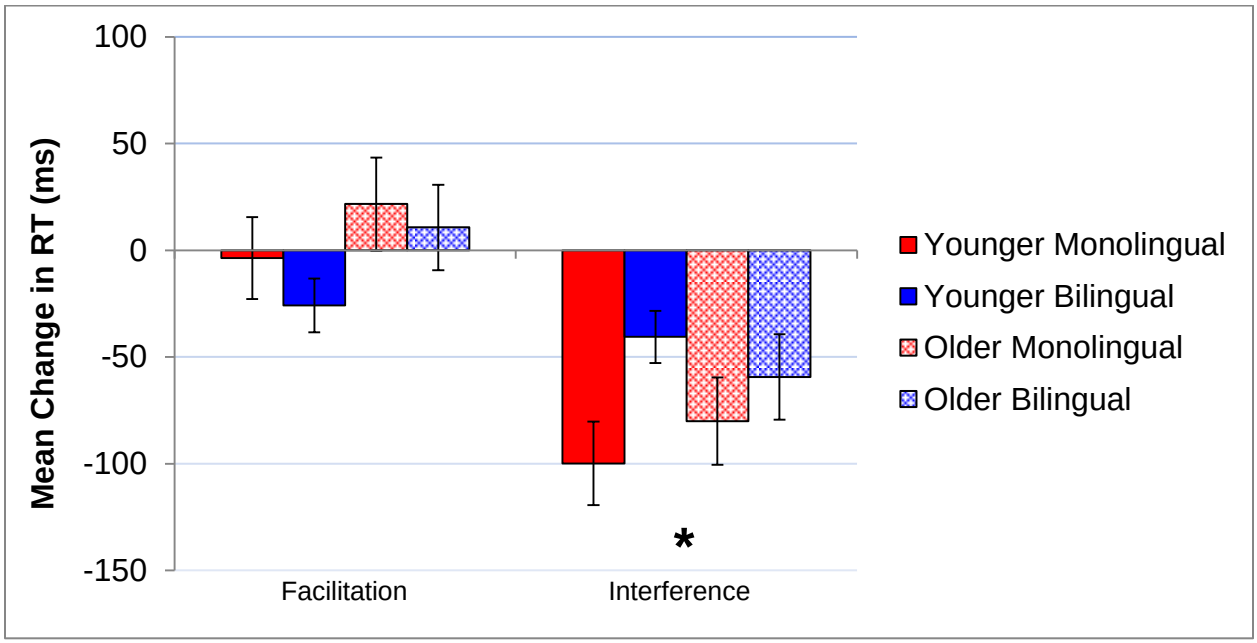


Figure 3. RT cost scores for facilitation and interference on the recent probe task by age and language group. Error bars represent standard errors.

A summary of the main findings for the three experimental tasks is shown in Table 6.

Table 6

Summary of Main Results by Experimental Task

	Age Group		Language Group	
Task	Simple Condition	Complex Condition	Simple Condition	Complex Condition
Star Counting	Y < O	Y < O	ML = BL	ML = BL
Modified Flanker	Y < O	Y < O	ML = BL	ML < BL
Recent Probe	Y < O	Y = O	ML = BL	ML > BL

Discussion

Both aging and bilingualism influenced performance on the three tasks used in the current study but the nature of the effects depended on the task (see Table 6). The participant groups were matched on relevant background measures with the exception of English vocabulary knowledge. This pattern of lower vocabulary scores in bilinguals and higher vocabulary scores in older adults, which is typical for the literature (e.g., Luo et al., 2013), had a significant impact on performance in the star counting task. As predicted, prior to controlling for vocabulary knowledge bilinguals were slower than monolinguals to count stars, even though participants were informed they could use the language in which they were most comfortable counting. The

groups were equivalent on counting accuracy for standard and working memory conditions, but the negative correlations between vocabulary and counting time reflect the verbal nature of this production task. Indeed, previous work has provided evidence that verbal memory and numerical working memory are part of the same construct (Oberauer, Süss, Schulze, Wilhelm, & Wittman, 2000). Once vocabulary was controlled, the main effect of bilingualism disappeared, but aging effects remained such that older adults were slower than younger adults. Thus, vocabulary was a factor in the slower task performance by bilinguals at both age groups but was not a factor in the slower performance by older adults in both language groups. Put another way, individuals became slower on this task with age but there was no evidence that performance was further moderated by language experience. The interaction of age with task conditions, such that older adults were slower than younger adults on conditions requiring the minimum level of executive control and the maximal level of executive control, suggests that in this largely processing based task, younger adults surpass older adults when the task relies more on basic speed of processing, but younger adults are also better able to handle the dual demands of high switching and remembering the complex counting rule than older adults.

For the modified flanker task, typical age-related slowing effects were seen for both the single arrow and conflict blocks, and older adults were particularly affected by the demands of having to remember to respond to the opposite arrow direction during conflict blocks. Single arrow blocks did not elicit any language group differences indicating no differences in simple speed of processing. However, monolinguals performed significantly faster than bilinguals on the conflict blocks, contrary to our expected results. Although we have no explanation for the difference shown on this version of the task other than the possibility that the bilinguals in the current sample attended more to the overall context of the conflicting cues (see explanation

below), the finding minimally demonstrates that the bilinguals were not inherently faster responders even on a simple conflict task.

Working memory during conflict trials on the modified flanker task was taken into account by calculating RT cost scores from having to remember the opposite response rule. There were no language group differences, reflecting equivalent effects of working memory on performance. The cues from the flanking arrows in this version of the task generate more conflict than in the traditional flanker task. For example, in the opposite direction condition congruent flankers are now opposite to the target response direction and therefore do not facilitate performance. This suggests that a greater amount of inhibition of flanking arrows is required for this version of the task, and undeniably, some of the older adults found this task to be particularly difficult and is in line with research showing that older adults have poorer inhibitory control than younger adults (Hasher, Zacks, & May, 1999). Therefore, successful performance on this task in contrast to the other tasks in the current study may be largely based on rapid inhibitory control processes more so than working memory ability.

The recent probe task was the same task as used in Bialystok et al. (2014), but the stimuli were more distinctive and easier to encode. Task accuracy declined with aging, but there were no effects or interactions with language. Similar accuracy rates across language groups allow for an interpretation of response processing without any speed-accuracy trade-offs. Additionally, participants consisted of healthy older and younger adults, without diagnosed memory impairment. For analyses of RTs, older adults were slower than younger adults, a result that was obviously expected. Crucially, however, bilinguals were faster than monolinguals on the proactive interference condition, replicating the finding in Bialystok et al. (2014). This indicates that when the need for conflict resolution in memory is high, (i.e., to overcome a strong sense of

familiarity and engage in accurate recollection), bilinguals are able to engage these processes more efficiently than monolinguals. The analyses of cost scores that represented the difference in time to respond to baseline and experimental trials for each of the positive and negative responses additionally showed that bilinguals had smaller interference costs than monolinguals, although the groups did not differ in the amount of facilitation effects from repeated trials. In fact, the facilitation effects were small (seen mainly for accuracy and not RT) so it is not surprising that there was no difference between groups on this measure. Aging and bilingualism did not interact, contrary to our initial prediction, indicating independent effects on working memory performance for this sample of healthy adults.

Together, these results indicate that the impact of bilingualism on working memory depends on task demands, namely the domain and presence of interference. Due to less efficient lexical access and retrieval, bilingual processing tends to be poorer than monolinguals for verbal tasks, unless vocabulary is controlled for, and this was seen both in the current study on the star counting task and previous work with verbal materials (e.g., Fernandes, Craik, Bialystok, & Kreuger, 2007). Bilinguals showed similar working memory costs as monolinguals on performance on the nonverbal modified flanker task, whereas better bilingual performance in working memory was tied to overcoming the influence of proactive interference supported by the results seen on the nonverbal recent probe task. This replication strengthens the findings from Bialystok et al. (2014) using a new set of nonverbal stimuli with an independent sample of younger and older bilingual and monolingual adults.

This work has implications for research involving bilingualism as a contributing factor to cognitive reserve in aging, and suggests that the underlying mechanism may be the ability to utilize the executive control system to deal with the detrimental effects of interference. The

current sample comprised healthy, well-educated adults. Future studies will need to assess whether enhanced nonverbal interference resolution in bilinguals remains stable through aging and investigate possible changes that accrue with the onset of neuropathology. In addition, the contributing role of working memory capacity versus processing in language group differences needs further exploration. The current study examined the role of working memory processing in the form of varying levels of executive control, however evidence from a recent meta-analysis also suggests that bilinguals may outperform monolinguals in terms of working memory capacity (Grundy & Timmer, 2017). There is also an existing literature on the role of working memory and L2 proficiency development and use. In a recent meta-analysis by Linck, Osthus, Koeth, and Bunting (2014), a positive relationship was shown between working memory and L2 outcomes, and stronger relationships were shown for complex working memory span tasks (i.e., greater need for executive control) than simple working memory span tasks and for verbal than nonverbal measures, providing evidence that the relationship between working memory and language development/use may be bidirectional. We conclude, however, by stating that bilingualism research is complex and accurate assessments of how bilingualism and aging influence working memory will depend on the level of bilingual experience, pre-existing abilities, and the task domain.

Chapter 3. Neural Correlates of Maintenance and Updating Processes in Working Memory

It is well established that aging is associated with memory decline and higher risk of dementia (Park & Festini, 2017). Behavioural results from studies investigating aging, bilingualism, and working as well as episodic memory have been mixed (Bialystok, Craik, Green, & Gollan, 2009) as to whether bilinguals show performance differences from monolinguals and if larger language group effects are present in older adults, indicating protection from age-related cognitive decline. Several researchers have suggested that memory tasks that are nonverbal and involve high levels of attentional control are associated with better bilingual performance than is found for monolinguals (Bialystok, Craik, Green, & Gollan, 2009; Calvo, Ibáñez, & García, 2016; Schroeder & Marian, 2014; Sullivan, Prescott, Goldberg, & Bialystok, 2016). The proposed role of attention in bilingual memory is due to the need for bilinguals to have some form of control over the dual activation of both languages (for reviews see Kroll & Bialystok, 2013; Kroll, Dussias, Bogulski, & Valdes-Kroff, 2012). Therefore, a general bilingual adaptation in selective attention (Bialystok, 2015) could extend into benefits for memory processing, however a model of bilingual memory must also take into consideration that bilinguals have difficulty with lexical retrieval during production tasks (e.g., for picture naming, Gollan, Montoya, Cera, & Sandoval, 2008; Sullivan, Poarch, & Bialystok, 2017; for verbal fluency, Bialystok, Craik, & Luk, 2008a; 2008b), as do older adults (Burke et al., 1991). It is currently unknown how bilingual memory is represented at the neural level in terms of both level of attention and stimulus domain. The aim of the current study is to address this gap in the literature, by recording event-related potentials (ERPs) as younger and older monolinguals and bilinguals perform a working memory task that varies in (1) whether the to-be-remembered

stimuli are verbal or nonverbal and (2) the amount of attentional control required to perform the memory task.

Memory for verbal information is generally poorer in bilinguals than monolinguals, without taking into account vocabulary knowledge and the cognitive demands of the task (Fernandes et al., 2007; Wodniecka et al., 2010). Work with bilingual autobiographical memory also indicates that in both younger (Marian & Neisser, 2000) and older adult bilinguals (Schrauf, 2000; Schrauf & Rubin, 1998; Schrauf & Rubin, 2000), that when the language at encoding matches the language at retrieval, recall is better. In contrast to memory for words, nonverbal memory, as with the use of pictures, elicits better recall in older bilingual than monolingual adults (Schroeder & Marian, 2012). In fact, performance differences between older adults and younger adults are smaller for memory tasks with pictures than words as the to-be-remembered stimuli, a finding that has been attributed to the ease with which deeper, more elaborative encoding can be engaged (for review see Craik & Rose, 2012; Craik & Schloerscheidt, 2011).

Further insight into how bilinguals may differ from monolinguals in terms of memory processing can be gathered from behavioural studies examining proactive interference. Proactive interference occurs when previously encoded information intrudes in memory (Jonides & Nee, 2006). In younger adults, monolinguals and bilinguals performed equivalently on a task of proactive interference involving recall of semantic category word lists; once English vocabulary was accounted for, the bilinguals displayed enhanced performance over monolinguals (Bialystok & Feng, 2009). The recent probe working memory task (Jonides & Nee, 2006) is used to assess the ability to overcome proactive interference as the contents of working memory must be rapidly updated from trial to trial. When younger and older adult monolinguals and bilinguals performed the task, age-related declines in performance were shown for both a verbal and

nonverbal version of the task. However, language group differences in performance were dependent on task domain. Bilinguals performed similarly to monolinguals when the task involved verbal stimuli, but bilinguals outperformed monolinguals, particularly in older adults, when the task was based on nonverbal stimuli (Bialystok, Poarch, Luo, & Craik, 2014). In the recent probe task, successful interference trials involved indicating that a probe item was not present in the most recent group of studied items, as the probe item had been present in a prior (n-1) trial designed to elicit interference. Better nonverbal interference resolution by bilinguals of both ages has since been replicated using different nonverbal stimuli (Chapter 2, Sullivan et al., 2016). These findings suggest that bilinguals are adept at dealing with nonverbal interference during updating processes in working memory.

Evidence from neural processing can be used to augment the interpretation of the results of behavioural studies. ERPs are an ideal methodology to look at the different components in the stream of memory processing, as the neural signal provides high temporal resolution in the range of milliseconds. More specifically, ERPs correspond to the summation of synchronized postsynaptic electrical activity from pyramidal neurons that are measurable at the scalp and are time-locked to cognitive events (Luck, 2005). By averaging over many trials of the recorded electroencephalogram (EEG) signal, reliable ERP components are separated from noise and consist of either a positive or negative voltage deflection occurring during a specific time window (e.g., the P3 or P300 ERP component is a positive voltage deflection occurring at approximately 300 ms post-stimulus). EEG data can also be examined in the frequency domain, whereby neural oscillations and synchronization can provide information about neuron-to-neuron communication (Roach & Mathalon, 2008).

The number of ERP studies examining working memory and bilingualism is currently limited. Prior EEG and other neuroimaging work has mainly focused on identifying how bilinguals represent lexical stimuli in memory through comparisons of L1 and L2 words, and have used young adult samples (e.g., Halsband, Krause, Sipilä, Teräs, & Laihinen, 2002 for PET; Xue, Dong, Jin, & Chen, 2004 for fMRI). For example, Leinonen, Laine, Laine, and Krause (2007) employed an auditory Sternberg memory task using highly proficient, balanced, early Finnish-Swedish young adult bilinguals while recording EEG to examine brain oscillatory responses of different frequencies that are elicited during encoding and retrieval processing. Four words are heard prior to the auditory presentation of a single word probe. The key manipulation was encoding and retrieval of words could be within- or between-languages, and the lexical items were all cognates (similar in meaning and orthography between languages). During encoding, greater theta and alpha synchronization and greater beta desynchronization were shown for Swedish stimuli than for Finnish stimuli. For between-language retrieval, delayed theta and alpha responses were shown and theta responses were larger than for within-language retrieval. The authors interpreted the neural signature shown for between-language retrieval as use of the executive control system to switch between languages, and the differences seen at encoding as the use of different strategies depending on the language used. Despite these neural changes, there were no differences at the behavioural level in memory performance across the different language conditions.

There is evidence however, that bilinguals and monolinguals differ in terms of the ERPs elicited during cognitive tasks involving attentional control. With a visual go-nogo task using shapes as stimuli that required response inhibition on less frequent nogo trials, it was shown that younger adult bilinguals experienced a larger N2 component and a larger late positivity

component (i.e., following the P3) than both monolingual musicians and monolingual non-musicians for nogo trials (Moreno, Wodniecka, Tays, Alain, & Bialystok, 2014). ERP differences were shown across the three groups even though there were no behavioural differences in reaction time (RT) or accuracy. In a comparable study where bilinguals and monolinguals performed an auditory, nonverbal go-nogo task, bilinguals had larger nogo N2 amplitude than monolinguals and similar behavioural performance (Fernandez, Tartar, Padron, & Acosta, 2013).

In another ERP study with young adults, bilinguals and monolinguals performed the AX-Continuous Performance Task (AX-CPT) (Morales, Yudes, Gómez-Ariza, & Bajo, 2015). In this task, pairs of letters are sequentially presented. When an A is followed by an X participants press 'yes' and this condition occurs frequently (i.e., 70% of trials). For the remaining 'no' conditions, AY trials that consist of an A followed by a non-X letter is a measure of proactive control as the initial cue to a 'yes' response must be overridden. For BX trials that consist of a non-A letter followed by an X, this is a measure of reactive control as the X probe to respond 'yes' must be overridden. Finally, BY trials that do not contain the letters A or X are used as a control/baseline condition. Behaviourally, the bilinguals produced fewer errors than monolinguals on all experimental trial types, with similar accuracy for BY trials. For the ERP results, there were no group differences to the cue letter, but bilinguals had larger N2 amplitude to the probe letter for AY (proactive) trials and showed a larger P3 difference between AY and BY (control) trials. These results indicate that for the most effortful trials, AY, bilinguals show increased neural processing to the probe letter to deal with proactive interference from the cue letter to correctly update their response. When a subset of the participants that were matched on AY accuracy were

examined, the probe ERP group differences disappeared, however there was a trend (p = .06) for a larger P3 difference between the A versus B cue in bilinguals than monolinguals.

For older adult bilinguals and monolinguals, ERP and behavioural differences have been shown to vary by the type of cognitive control task. Kousaie and Phillips (2017) recorded ERPs while older adult bilinguals and monolinguals performed the Stroop, Simon, and flanker task. The bilinguals were more accurate and showed larger mean P3 amplitude than monolinguals for the incongruent conflict trials of the Stroop task, where colour names are printed in different colour font. Bilinguals also displayed an earlier elicited N2 component than monolinguals for congruent trials, suggesting faster initiation of conflict monitoring. The remaining tasks showed no behavioural differences across language groups. For the Simon task, which measures stimulus-response compatibility, monolinguals exhibited a larger N2, but bilinguals showed a larger P3 component and earlier P3 latency. Finally, for the flanker task, monolinguals displayed larger N2 amplitude for conflict trials, whereas bilinguals showed similar N2 amplitude across trials, but faster latency for the N2 on conflict trials and for the P3 on congruent trials. Thus, older adult bilinguals and monolinguals appeared to use different neural processing mechanisms across a variety of conflict tasks, independently of whether or not behavioural performance differed.

The P3 component that was just described in relation to cognitive control tasks has also been shown to be elicited during memory processing (Amin, Malik, Kamel, Chooi, & Hussain, 2015; Donchin, 1981). P3 amplitude distinguishes maintenance/storage from updating components of working memory (Kiss, Watter, Heisz, & Shedden, 2007; Polich & Kok, 1995; Watter, Heisz, Karle, Shedden, & Kiss, 2010), and has a role in stimulus categorization (Mecklinger & Ullsperger, 1993). There is evidence for two subcomponents of the P3, consisting

of a more frontal P3a attentional mechanism and a temporal-parietal P3b associated with attention and memory processing (Polich, 2007). There is currently a lack of research examining the impact of bilingualism on the P3 during tasks of working memory, although studies have been conducted in relation to how the P3 changes with aging.

For example, Saliasi, Geerligs, Lorist, and Maurits (2013) investigated how the P3 changes with age when older and younger adults performed working memory N-back tasks. Participants were required to respond to either the appearance of an 'x' (0-back condition) or determine if the letter on the screen matched the previous letter (1-back condition) requiring greater attention to update the contents of working memory. More effortful conditions had a larger impact on older adult than younger adult performance. Older adults had a larger frontal P3 and a lower parietal P3 than younger adults, and a longer P3 latency. In younger adults, a higher parietal P3 was linked to better performance, and more effortful conditions elicited a larger P3. Older adults displayed similar P3 amplitude across the 0-back and 1-back versions, and higher P3 amplitude at both frontal and parietal locations was not optimal for older adult performance. These findings of a decline in parietal activity, a shift towards greater frontal activity, and increased latency in ERP components appear common for studies on memory and aging using ERP (Fjell, Walhovd, & Reinvang, 2005 for verbal recognition; McEvoy, Pellouchoud, Smith, & Gevins, 2001; Müller & Knight, 2002 for spatial working memory), and indicates the presence of brain functional reorganization of the P3 with aging.

As discussed in Chapter 1, the P3 component indexes attentional control in working memory and prior work suggests it functions in a similar manner across stimulus domains (McEvoy et al., 1998; Shucard et al., 2009). The findings from the bilingualism and cognitive control literature indicate that bilinguals typically have larger P3 amplitude than monolinguals

for effortful conditions, however this effect has not been examined in relation to attentional control in working memory. It is also unknown if bilinguals and monolinguals will exhibit different levels of P3 amplitude associated with working memory task domain. The aim of the current study was to use ERPs to investigate the neural correlates of language experience and aging for attention and working memory as indexed by the P3 component. The selected task was from the ERP study conducted by Watter et al. (2010). The running memory procedure used by Watter and colleagues is an ideal design for investigating attention in working memory and across domains. In the verbal task participants are required to remember digit identity and in the spatial task participants are required to remember digit position. The level of attention in working memory depends on whether participants are instructed to maintain the items in working memory or update the items in working memory requiring more effortful control.

Watter et al. (2010) studied young adult participants and found that both RTs and error rates were highest for the update condition, followed by maintenance, and lowest for the control condition. ERP waveforms were examined during the study phase and were time-locked to the serial positions of the presented items. Average mean amplitudes in a centroparietal region of interest (ROI) were analyzed during a 300 to 450 ms time window, representing the P3 component. The P3 component was present for the maintenance and update conditions, but not the control condition, with larger amplitudes seen for verbal than for spatial working memory. For the maintenance condition, amplitudes were strongest and grew larger over serial positions 1 to 3 and then substantially decreased for the following items in the series, as participants were only required to remember the first three items in working memory. For the update condition, participants were required to remember the last three items in the series and thus needed to continually update the contents of working memory. During updating, consistent amplitudes that

were above the control condition were shown across serial positions, indicating the relevance of the P3 for attention in memory. These results were found for the study phase in working memory, however Watter et al. (2010) did not analyze the ERP data during recognition processing at the memory probe where the response decision is made.

The current investigation examined P3 amplitude in terms of both the study phase and recognition in working memory. It was predicted that for varying levels of attention in working memory, bilinguals will perform better than monolinguals on more effortful conditions and for nonverbal stimuli (i.e., update/spatial). Typical age group effects of slower RT and lower accuracy for older adults than younger adults are expected. Poorer performance is predicted for older adults in particular for spatial working memory as it has been shown by Hale and colleagues (2011) that there are greater age-related declines in performance on spatial span tasks than performance on verbal span tasks (see also, Luo, Craik, Moreno, & Bialystok, 2013 with older adult bilinguals and monolinguals). Group differences should be evident at the electrophysiological level for mean P3 amplitude. At the initial study phase, the Watter et al. (2010) task effects should replicate, with P3 amplitude increasing the more effortful the condition. Both language and age group differences are expected at the decision stage for the recognition probe. Age effects should replicate prior recognition research showing a diminished centroparietal P3 and a larger more frontal P3 for older than younger adults. Bilinguals are expected to show larger centroparietal P3 amplitude than monolinguals at recognition for the nonverbal, update condition demonstrating a better allocation of attentional resources, whereas this language group effect may be diminished for the verbal task supporting work that bilinguals have difficulty with lexical retrieval. This design will allow greater insight into the neural mechanisms of how aging and bilingualism impact attentional control in working memory.

Method

Participants

A total of 112 right-handed participants, consisting of older and younger adults who were either monolingual or bilingual took part in the current study. Younger adults were undergraduate students from York University, Toronto, Canada, and older adults were from the community. Participants were excluded if EEG data was unusable due to excessive noise/drift or if the working memory task could not be completed. This resulted in loss of data for one older monolingual for spatial and verbal, one older monolingual for spatial, one younger bilingual for spatial and verbal, one younger bilingual for spatial, and one younger bilingual for verbal. The final younger sample included 54 participants between the ages of 18 and 29 (M = 21.1, SD = 3.3) of whom 26 were monolingual English speakers and 28 were bilinguals who reported being fluent in English and at least one other language[5]. The final older adults sample consisted of 56 participants between the ages of 66 and 83 (M = 73.8, SD = 4.6) of whom 26 were English monolinguals and 30 were bilinguals[6].

Background Measures

Participants completed the Language and Social Background Questionnaire (LSBQ; Anderson, Mak, Keyvani Chahi, & Bialystok, 2018; Luk & Bialystok, 2013) to obtain information about language experience. As a newer version of the LSBQ was used than reported in Chapter 2, scales range from 1–10 instead of 1–100, however comparable language background information is assessed. Similar to the study in Chapter 2, vocabulary and nonverbal

[5] The non-English languages of the younger adult bilinguals included Arabic (2), Assyrian (1), Cantonese (2), Farsi (4), Filipino (1), French (1), Gujarati (1), Hebrew (1), Mandarin (3), Persian (1), Portuguese (1), Punjabi (2), Spanish (1), Tamil (2), Twi (1), Urdu (3), and Vietnamese (1).

[6] The non-English languages of the older adult bilinguals included Afrikaans (1), Cantonese (1), French (5), Fukien (1), German (3), Hindi (1), Hungarian (2), Italian (2), Maltese (1), Marathi (1), Polish (1), Russian (1), Sindhi (1), Singhalese (1), Spanish (1), Tagalog (2), Tamil (1), Ukrainian (1), Urdu (1), and Yiddish (2).

fluid intelligence were assessed by the paper-based versions of the Shipley-2 Institute of Living Scale- Vocabulary and Block Patterns Scales (Shipley, Gruber, Martin, & Klein, 2009).

Tasks

Working memory ERP task. This running memory procedure allows for an item-by-item investigation of study and recognition processes in working memory and contains conditions requiring varying levels of attention. The stimuli are from the Watter et al. (2010) study (see Appendix D). For the study phase, participants are shown a display of eight small white boxes positioned on the outer sides of a larger white box, such that there are two smaller boxes per side of the larger box in a grid-like format. A series of these displays is presented one at time with a number appearing randomly in one of the outer boxes. For both the verbal and spatial versions of the task, the study series consists of a set size of 4 to 7 digits (1-9) appearing in succession and presented in white 36-point Helvetica font against a black background.

For the spatial recognition phase, participants saw a display with shaded boxes around the center box after the series of digits were presented. The decision made at the probe was based on the instruction given at the start of the trial. When the instruction was 'Look for SET of 3 positions', the task was to determine if 3 squares were shaded in. This was the control condition because there was no memory requirement. When instruction 'Remember the FIRST 3 positions' appeared, the task was to decide if the shaded squares at the end of the sequence matched the positions of the FIRST three numbers presented in the sequence. This was the maintenance condition, as participants were required to maintain the positions of the initial three stimuli in working memory. When the instruction 'Remember the LAST 3 positions' appeared, the task was to decide if the shaded squares at the end of the sequence matched the positions of the LAST three numbers in the sequence. This was the update condition, as participants had to continually

update the contents of the last three stimuli in working memory and required the most effort and level of attentional control.

For the verbal recognition phase, participants saw a display with three items in the center box that appeared after the completion of the study series. When the instruction was 'Look for a SET of 3 numbers', the task was to determine whether the 3 items were all numbers and there was no memory requirement. When the instruction 'Remember the FIRST 3 numbers' appeared, the task was to decide if the numbers in the center box were the FIRST three numbers in the series and represented the maintenance condition. Finally, when the instruction 'Remember the LAST 3 numbers' appeared, the task was to decide if the numbers in the center box at the end of the series were the LAST three numbers in the series. In summary, participants are required to remember either digit position (spatial task) or digit identity (verbal task).

For each task, participants completed 8 blocks of 5 trials per condition (i.e., control, maintenance, update) for a total of 40 trials per condition. Block presentation was a fixed order Latin Square Design: 123, 231, 312, 123, 231, 312, 123, 231, where 1 represents control, 2 represents maintenance, and 3 represents update. A set size of 4, 5, 6, or 7 items in a trial-study sequence had a random presentation per block with a probability of: 1/7 = 14% for set size 4; 2/7 = 29% for each of set sizes 5, 6, 7. This probability ratio was used as the smaller set size of 4 items ensures participants are paying attention to the numbers presented earlier in the series, however the presentation of the longer set sizes allows for updating processes to be examined. The number of targets versus non-targets for the memory decision probe was randomly presented per block. Participants responded with their index fingers using the inside press of the left and right mouse. The response designation for each mouse was specified in the instructions given before the task and was counterbalanced across participants.

The timing parameters for the task were as follows: each digit was presented for 200 ms, followed by a white fixation cross contained within the center of the grid with a jittered presentation of 1000 to 1300 ms (timing from Watter et al., 2010's young adult study). A start delay of 500 ms was included prior to each digit presentation to ensure that participants had enough time after responding to the probe to attend to the first item in the next series and to create a longer ISI to make the task more manageable for the older adult participants. The recognition probe remained on the screen until the participant responded or after a length of 2000 ms (see Appendix E).

Procedure

Participants completed all tasks within a single 2 to 2.5-hour session depending on the length of the EEG setup. Similar to the study presented in Chapter 2, upon arrival, participants completed the consent form and the LSBQ in the behavioural testing room. The experimenter administered the Shipley-2 Vocabulary and Shipley-2 Block Patterns Scales according to standardized instructions. The participant was then moved into the EEG testing room for set-up of the cap and electrodes. Participants were seated in a dimly lit room with their eyes approximately 50 cm from the screen and with their hands able to comfortably reach both mice and the keyboard. The working memory tasks were completed on a Dell OptiPlex 760 desktop using Presentation software package (Presentation 14.6, Neurobehavioral Systems, Inc.) and each task was approximately 30 min in length. The order of the verbal and spatial tasks was counterbalanced across participants. Prior to each version of the working memory task, the experimenter went through a single practice block of 5 trials for each condition. The participant had the opportunity to repeat the practice trials if needed. Between each working memory task there was a 5 min break. At the end of the experiment participants were debriefed and were

compensated $40 for their time (older adults) or given course credit (younger adults).

ERP Recording and Preprocessing

The electroencephalogram (EEG) was continuously recorded using a Biosemi amplifier system (Amsterdam, BioSemi Active 2) from an array of 64 active Ag-AgCl electrodes located at standard positions (International 10/20 system sites) and digitized at a sampling rate of 512 Hz. During the recording, all electrodes are referenced to the CMS (Common Mode Sense) electrode, with the DRL (Driven Right Leg) electrode serving as the ground. Impedances of the electrodes were kept at or below 20 kΩ or otherwise noted. The EEG system and each step of the set-up procedure were explained to each participant. Facial electrodes were placed approximately 1 cm from the outer canthi (corner of the eye where upper and lower eyelids meet), below the left and right eye, and attached to the left and right mastoid.

EEG data were analyzed off-line using EEGLAB and ERPLAB (MATLAB Toolbox, SCCN). An offline bandpass filter of 0.1-55 Hz was used and data were re-referenced to a common average reference. This filter range was selected as an optimal setting based on prior research using multiscale entropy (MSE) analysis (Heisz, Gould, & McIntosh, 2015; Heisz, Shedden, & McIntosh, 2012). Continuous EEG was segmented into 1200 ms epochs from a 200 ms prestimulus baseline to 1000 ms after stimulus onset (i.e., to each study item position or to the memory recognition probe). Artifact removal was based on independent component analysis (ICA) denoising using EEGLAB. Components representing ocular and muscle artifacts were removed from the data. ERPs were averaged separately for each task domain (spatial or verbal) for correct trials only. For study processing, following the procedures done by Watter et al. (2010), ERPs were time locked per condition (control, maintenance, update) to each serial position (1-7) in the study sequence, using a weighted average across set sizes and targets and

non-targets. For probe recognition processing, ERPs were time locked per condition (control, maintenance, update) to the probe across all set sizes, with a weighted average across targets and non-targets.

ERP Analysis ROIs and Time Windows

Study processing was analyzed in terms of P3 mean amplitude from a centroparietal ROI, consisting of the electrodes: C1, Cz, C2, CP1, CPz, CP2, and Pz, and during a time window of 300 to 450 ms. Probe recognition processing was analyzed in terms of P3 mean amplitude from a frontocentral ROI, consisting of the electrodes F1, Fz, F2, FC1, FCz, and FC2, and from a centroparietal ROI, consisting of the electrodes C1, Cz, C2, CP1, CPz, CP2, and Pz, and during a time window of 300 to 450 ms.

Results

Background Measures

Two-way ANOVAs for age group and language group were run on the background measures reported in Table 7. For participant age in years, there was an expected main effect of age group, $F(1, 106) = 4671.91$, $p < .0001$, $\eta^2_p = .98$, but no main effect or interaction with language group, Fs < 1. There were no group differences on nonverbal intelligence scores, Fs < 2.1. English receptive vocabulary scores were significantly higher in older adults than younger adults, $F(1,105) = 15.47$, $p = .0002$, $\eta^2_p = .13$, and higher in monolinguals than in bilinguals, $F(1,105) = 8.54$, $p = .0043$, $\eta^2_p = .08$, with no significant interaction, $F < 1.2$. As younger and older adult education was measured on different scales, one-way ANOVAs were run for each age group to assess potential language group differences. For both younger and older adults, there was no difference between language groups on education, Fs < 1. Table 7 also displays

language proficiency and usage information collected from the LSBQ, representing the language profiles of participants.

Table 7.

Means (and SDs) of Background Variables by Age Group and Language Group

Age	Younger Adults		Older Adults	
Group	Monolinguals	Bilinguals	Monolinguals	Bilinguals
N	26	28[a]	26	30
Sex	15 F, 11 M	21 F, 7 M	18 F, 8 M	17 F, 13 M
Handedness	26 R	28 R	26 R	30 R
Age (years)	20.9 (3.5)	21.3 (3.1)	74.0 (4.1)	73.6 (5.1)
Education[b]	13.3 (2.2)	13.6 (1.3)	3.8 (0.9)	4.0 (1.0)
Nonverbal Intelligence	103.5 (9.6)	100.0 (13.6)	105.3 (14.2)	101.6 (13.4)
English Vocabulary	104.3 (11.1)	96.4 (12.2)	109.9 (6.2)	106.3 (10.6)
LSBQ Self-Ratings[c]				
English Proficiency	10.0 (0.2)	9.4 (1.0)	9.8 (0.5)	9.6 (0.8)
English Usage	10.0 (0.0)	7.2 (1.9)	10.0 (0.0)	8.7 (1.3)
Non-English Proficiency	1.1 (1.1)	9.0 (1.1)	1.2 (1.1)	8.5 (1.7)
Non-English Usage	0.1 (0.4)	5.4 (2.1)	0.1 (0.4)	2.5 (2.5)

Notes. [a]One younger bilingual did not complete the Shipley Vocabulary Scale (n = 27) and another younger bilingual did not complete the Shipley Block Patterns Scale (n = 27). [b]Education: Younger adults = years, Older adults = ranges from 0-5, where '3' is some post-secondary education and '4' is post-secondary degree/diploma. [c]Self-report ratings of proficiency range from 0 = "No proficiency" and 10 = "High proficiency" and usage from 0 = "Never" and 10 = "Always". Proficiency ratings were based on an average of speaking and understanding. Usage

ratings were based on an average of speaking and listening. Sex: F – Female, M – Male. Handedness: R – Right, L – Left, A – Ambidextrous.

Working Memory: Behavioural Results

For each domain (spatial or verbal), a three-way repeated measures ANOVA was run on accuracy and RT measures, with age group and language group as the between-subjects variables and condition (control, maintenance, update) as the within-subjects variable. For all statistical analyses, if the Greenhouse-Geisser estimates of sphericity (ϵ) < .75 then the Greenhouse-Geisser correction was used for significant violations of sphericity. If the Greenhouse-Geisser estimates of sphericity (ϵ) > .75 then the Huynh-Feldt correction was used for significant violations of sphericity to ensure the correction is not too conservative (Field, 2009; Girden, 1992). Accuracy measures are presented in Table 8 by group and condition. RT measures are presented in Figures 4 (spatial) and 5 (verbal).

For accuracy measures in the spatial task, younger adults were more accurate than older adults, $F(1, 104) = 16.87$, $p < .0001$, $\eta^2_p = .14$, with no main effect or interaction with language group, Fs < 2 (see Table 8). There was a main effect of condition, $F(1.66, 172.64) = 33.71$, $p < .0001$, $\eta^2_p = .24$, $\epsilon = .83$. Contrasts ($\alpha_{corrected} = (.05/2) = .025$) indicated that control accuracy was higher than maintenance, $F(1, 107) = 12.03$, $p = .0008$, $\eta^2_p = .10$, and that maintenance accuracy was higher than update accuracy, $F(1, 107) = 35.53$, $p < .0001$, $\eta^2_p = .25$. There was also a condition by age group interaction, $F(1.66, 172.64) = 3.15$, $p = .055$ ($p < .05$, uncorrected), $\eta^2_p = .03$, $\epsilon = .83$. Univariate analyses indicated that there was a significant effect of age in all three conditions but that the effect size was larger for the more difficult conditions (control, $F(1, 104) = 5.38$, $p = .022$, $\eta^2_p = .05$, maintenance, $F(1, 104) = 8.87$, $p = .0036$, $\eta^2_p = .08$, and update

condition, $F(1, 104) = 22.23$, $p < .0001$, $\eta^2_p = .18$.) (see Table 8). There were no other group interactions with condition, Fs < 1.

The main effects for verbal accuracy paralleled the findings from the spatial task. Age-related declines were present, as younger adults were more accurate than older adults, $F(1, 105) = 6.34$, $p = .0133$, $\eta^2_p = .06$, with no main effect or interaction with language group, Fs < 2 (see Table 8). Accuracy was influenced by condition, $F(1.82, 191.10) = 26.89$, $p < .0001$, $\eta^2_p = .20$, $\epsilon = .91$. Contrasts ($\alpha_{corrected} = (.05/2) = .025$) again signaled that control accuracy was higher than maintenance accuracy, $F(1, 108) = 19.71$, $p < .0001$, $\eta^2_p = .15$, and that maintenance accuracy was higher than update accuracy, $F(1, 108) = 8.60$, $p = .0041$, $\eta^2_p = .07$. Unlike the results seen for the spatial task, there were no interactions with group and condition, Fs < 2.2.

Table 8.

Mean Accuracy as Proportion Correct (and SDs) by Group for Spatial and Verbal Working Memory Conditions

	Younger Adults		Older Adults	
Condition	Monolinguals	Bilinguals	Monolinguals	Bilinguals
n	26	27 (Spatial) 27 (Verbal)	25 (Spatial) 26 (Verbal)	30
Spatial Control	0.97 (0.05)	0.93 (0.11)	0.91 (0.15)	0.88 (0.16)
Spatial Maintenance	0.92 (0.08)	0.91 (0.10)	0.85 (0.16)	0.81 (0.23)
Spatial Update	0.89 (0.09)	0.86 (0.08)	0.77 (0.14)	0.73 (0.19)
Verbal Control	0.96 (0.11)	0.96 (0.08)	0.93 (0.13)	0.92 (0.14)
Verbal Maintenance	0.93 (0.07)	0.88 (0.12)	0.90 (0.11)	0.85 (0.17)
Verbal Update	0.90 (0.10)	0.89 (0.09)	0.83 (0.11)	0.82 (0.15)

For reaction time measures of spatial processing, older adults were slower to respond than younger adults, $F(1, 104) = 83.64$, $p < .0001$, $\eta^2_p = .45$, with no main effect or interaction with language group, Fs < 2 (see Figure 4). There was a significant main effect of condition, $F(1.74, 180.96) = 125.41$, $p < .0001$, $\eta^2_p = .55$, $\epsilon = .87$. Contrasts ($\alpha_{corrected} = (.05/2) = .025$) indicated that the overall RT for the control condition was faster than the maintenance condition, $F(1, 107) = 21.59$, $p < .0001$, $\eta^2_p = .17$, and that maintenance RT was faster than update RT, $F(1, 107) = 159.09$, $p < .0001$, $\eta^2_p = .60$. There was also a significant interaction of condition by age group, $F(1.74, 180.96) = 6.16$, $p = .0039$, $\eta^2_p = .06$, $\epsilon = .87$. Univariate analyses indicated that there was a significant effect of age for the control, $F(1, 104) = 43.72$, $p < .0001$, $\eta^2_p = .30$, maintenance, $F(1, 104) = 58.95$, $p < .0001$, $\eta^2_p = .36$, and update conditions, $F(1, 104) = 69.15$, $p < .0001$, $\eta^2_p = .40$. In addition, collapsing across language, younger, $F(1.46, 75.92) = 62.60$, $p < .0001$, $\eta^2_p = .55$, $\epsilon = .73$, and older adults, $F(1.88, 101.52) = 70.20$, $p < .0001$, $\eta^2_p = .57$, $\epsilon = .94$, each displayed a significant effect of condition. Therefore, as was shown for spatial accuracy, the age by condition interaction can be attributed to the fact that the effect size due to age becomes larger the more effortful the condition (see Figure 4). There were no other group interactions with condition, Fs < 1.

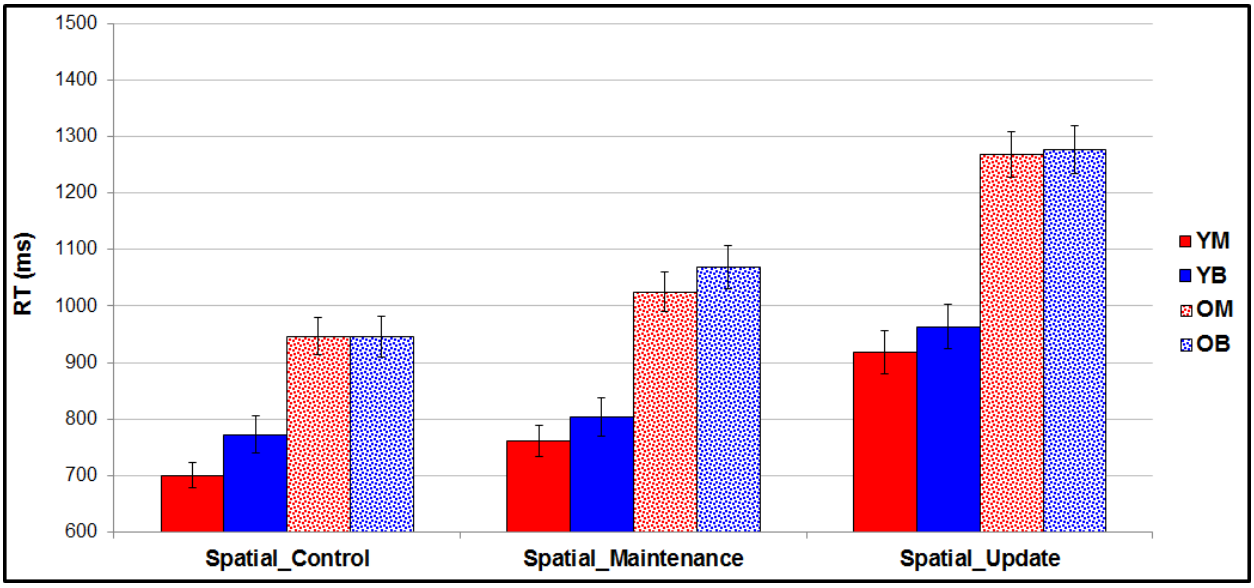


Figure 4. Mean RT by group and condition for spatial working memory processing. Error bars represent standard error.

Aging also impacted the speed of verbal processing, and older adults were slower to respond than younger adults, $F(1, 105) = 27.38$, $p < .0001$, $\eta^2_p = .21$, with no main effect or interaction with language group, Fs < 1 (see Figure 5). Similar to the spatial task, there was a graded effect of condition, $F(1.56, 163.80) = 277.22$, $p < .0001$, $\eta^2_p = .73$, $\epsilon = .78$. Contrasts ($\alpha_{corrected} = (.05/2) = .025$) indicated that control RT was faster than maintenance RT, $F(1, 108) = 106.48$, $p < .0001$, $\eta^2_p = .50$, and that maintenance RT was faster than update RT, $F(1, 108) = 234.18$, $p < .0001$, $\eta^2_p = .68$. The verbal task also showed a significant interaction of condition by age group, $F(1.56, 163.80) = 6.81$, $p = .0033$, $\eta^2_p = .06$, $\epsilon = .78$. Univariate analyses indicated that there was a significant effect of age for the control, $F(1, 105) = 26.40$, $p < .0001$, $\eta^2_p = .20$, maintenance, $F(1, 105) = 9.06$, $p = .0033$, $\eta^2_p = .08$, and update condition, $F(1, 105) = 26.59$, $p < .0001$, $\eta^2_p = .20$. Again, collapsing across language, younger, $F(1.44, 74.88) = 150.55$, $p < .0001$, $\eta^2_p = .74$, $\epsilon = .72$, and older adults, $F(2, 110) = 144.02$, $p < .0001$, $\eta^2_p = .72$, $\epsilon = .78$, each

displayed a significant effect of condition. Therefore, the age by condition interaction can be attributed to the fact that the effect size due to age is larger for the control and update condition in comparison to the maintenance condition (see Figure 5). The gap between older adult and younger adult performance for verbal maintenance appears to be closer than what was seen with spatial maintenance (see Figures 4 and 5) There were no other group interactions with condition, *F*s < 1.

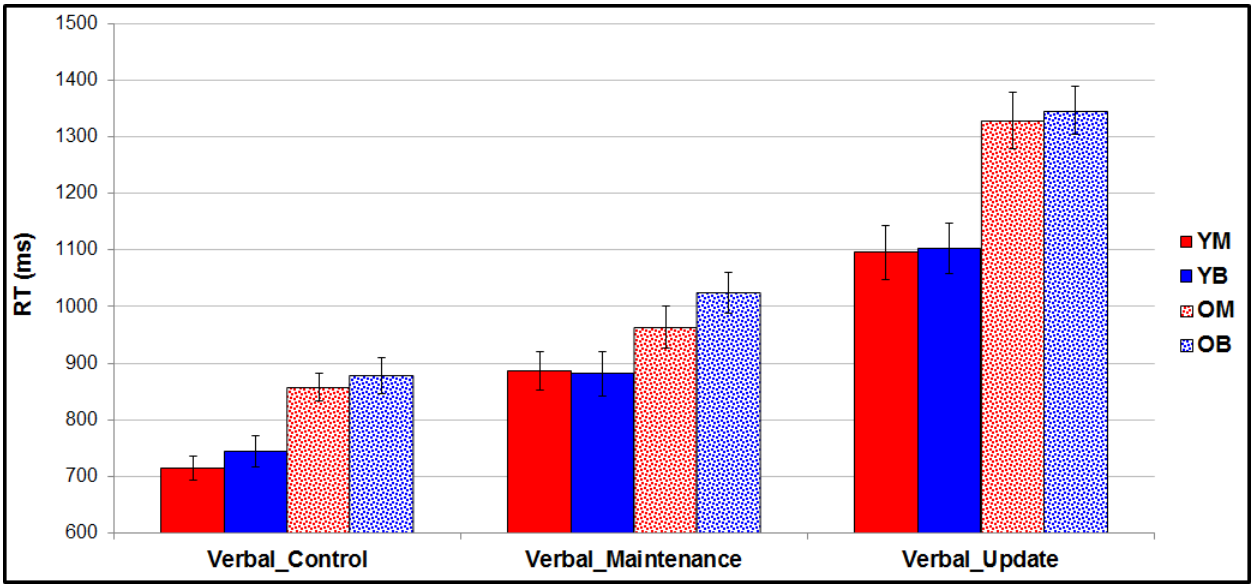


Figure 5. Mean RT by group and condition for verbal working memory processing. Error bars represent standard error.

Summary of Working Memory Behavioural Results

Clear task effects were shown across spatial and verbal domains. More effortful conditions resulted in longer RTs and lower accuracy, replicating previous research (Watter et al., 2010). As expected, aging resulted in longer RTs and lower accuracy, however several interactions with condition were present. For spatial accuracy, the largest age-related decline in

accuracy was shown for the update condition. This age by condition interaction was not shown for verbal accuracy. For spatial RT, the effect of aging was larger the more effortful the condition. For verbal RT, the effect of aging was larger for the control and update conditions than for the maintenance condition.

Working Memory: ERP Results

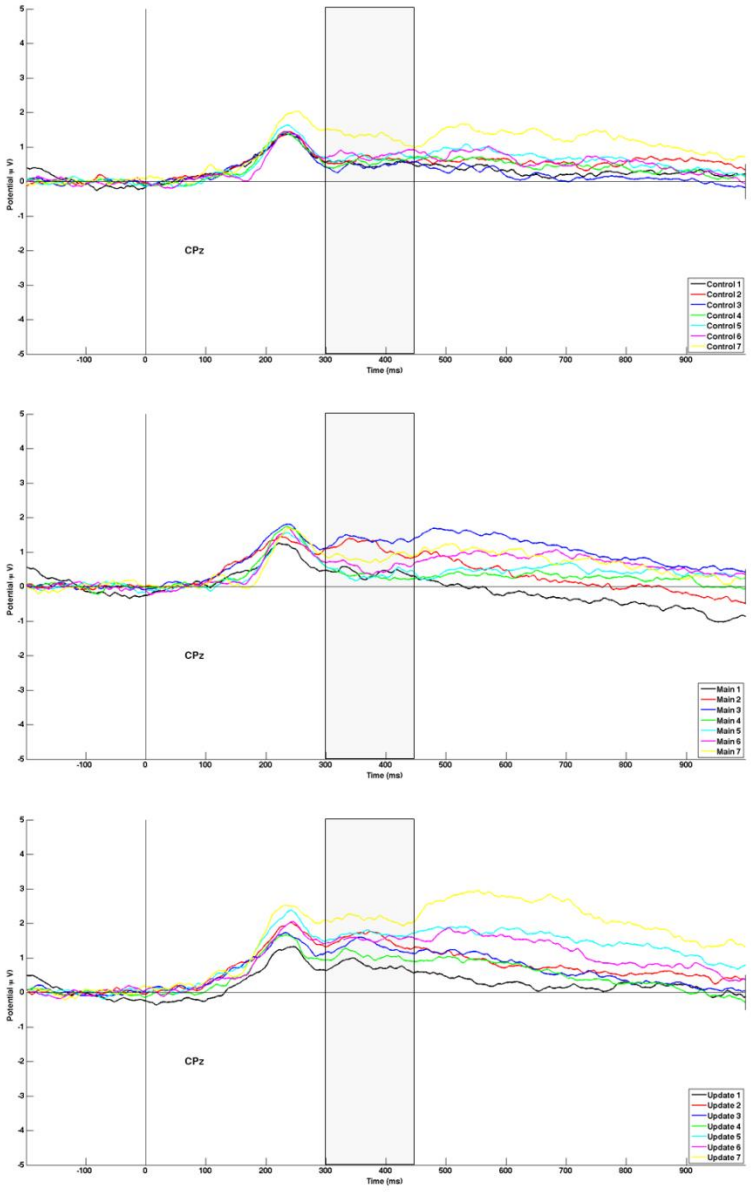
Study Phase Mean Amplitude: Centroparietal P3 (300 to 450 ms)

For each domain (spatial or verbal), a four-way repeated measures ANOVA was performed on P3 mean amplitude, with age group and language group as the between-subjects variables and condition (control, maintenance, update) and serial position (1–7) in the study phase as the within-subjects variables. This procedure of time-locking P3 amplitude to each serial position in the study sequence was performed by Watter et al. (2010). The relevance of examining serial position is to assess how attentional resources are allocated during the study phase. In the maintenance condition, P3 amplitude should be highest for the first three items than for the rest of the series as these items had to be stored in working memory. For the update condition, P3 amplitude should be stable across all serial positions as attention was required throughout the series to continually update the contents of working memory. P3 amplitude should be weaker across all serial positions in the control condition, as the stimuli were not relevant to final response. The ROI for the study phase consisted of the average amplitude across seven centroparietal electrodes C1, Cz, C2, CP1, CPz, CP2, and Pz to coincide with Watter et al. (2010).

The spatial study phase was dominated by task effects (see Figure 6). There was a significant main effect of condition on P3 amplitude, $F(1.70, 176.80) = 49.97$, $p < .0001$, $\eta^2_p = .32$, $\epsilon = .85$. Overall amplitude for the maintenance condition did not statistically differ from the

control condition, $F < 1$, but update amplitude was larger than control, $F(1, 107) = 57.88$, $p < .0001$, $\eta^2_p = .35$, and maintenance, $F(1, 107) = 64.03$, $p < .0001$, $\eta^2_p = .37$ (contrast αcorrection = (.05/3) = .0167). P3 amplitude varied by serial position, $F(3.96, 411.84) = 12.86$, $p < .0001$, $\eta^2_p = .11$, $\epsilon = .66$, and there was a significant interaction of condition by position, $F(4.32, 449.28) = 7.03$, $p < .0001$, $\eta^2_p = .06$, $\epsilon = .36$. As shown in Figure 6, this was mainly due to an increase in P3 amplitude for the maintenance condition from positions 1 to 2 and a subsequent decrease in amplitude from positions 3 to 4, indicating the relevance of the P3 for studying the first three items and replicates the results from Watter et al. (2010). In terms of group differences for the spatial study phase, there was a marginal main effect of age, $F(1, 104) = 3.27$, $p = .07$, $\eta^2_p = .03$, with older adults showing an overall larger P3 amplitude than younger adults (see Figure 6, panel B). There was no main effect of language or interaction with age group, Fs < 1. There were no significant group interactions with condition or position, Fs < 1.7.

A


CPz
Potential (μ V)
Time (ms)
Control 1
Control 2
Control 3
Control 4
Control 5
Control 6
Control 7
CPz
Potential (μ V)
Time (ms)
Main 1
Main 2
Main 3
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Update 1
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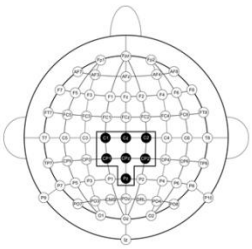
Update 4
Update 5
Update 6
Update 7



B

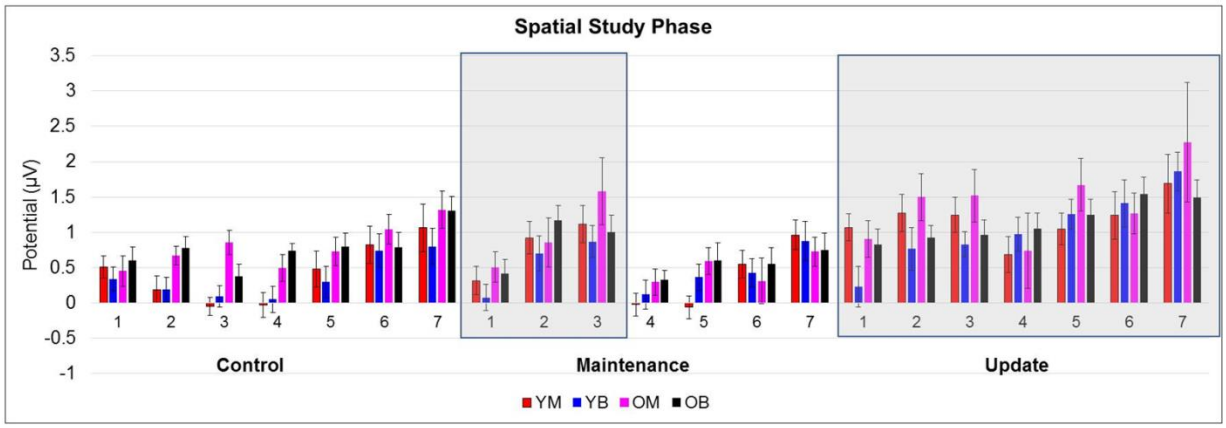
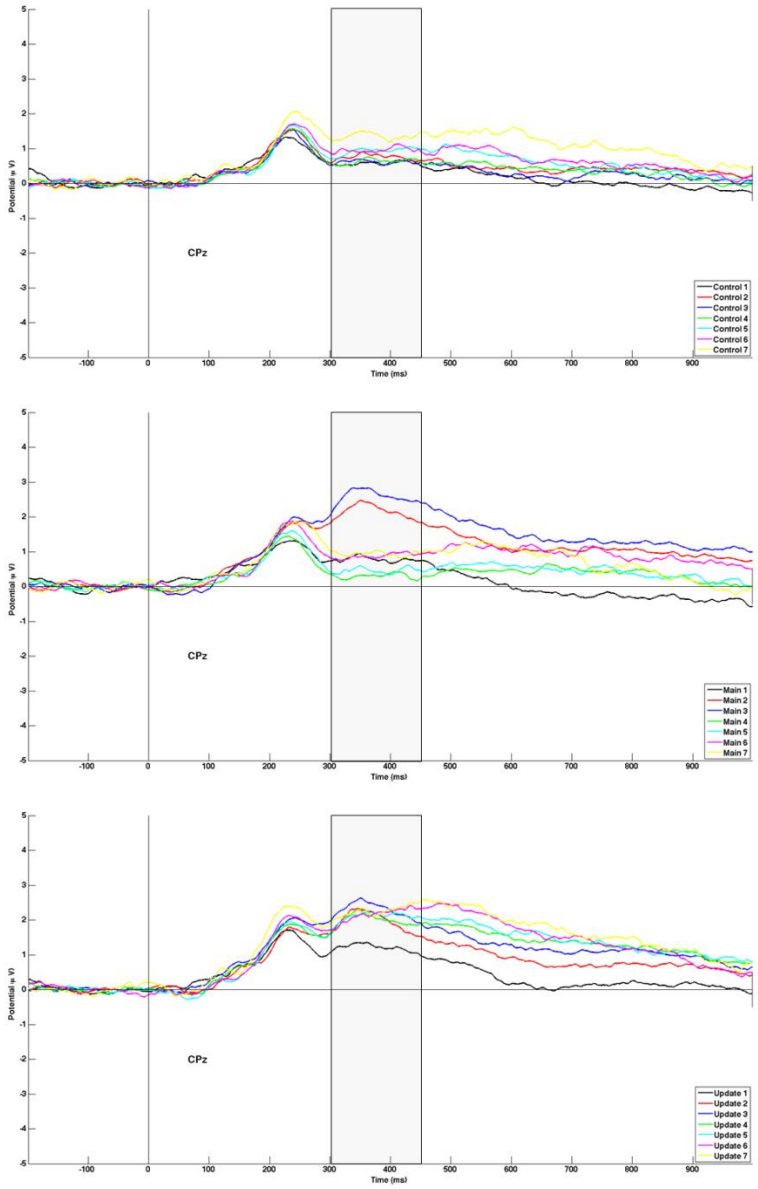

Spatial Study Phase
Potential (μV)
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
1 2 3 4 5 6 7 1 2 3 4 5 6 7 1 2 3 4 5 6 7
Control
Maintenance
Update
YM YB OM OB

Figure 6. Grand averaged waveforms for item serial position 1-7 from the spatial study phase are presented by condition (top- control, middle- maintenance, bottom- update) for the representative electrode, CPz (panel A). The P3 time window of 300 to 450 ms is highlighted by the grey box. The bar graph (panel B) depicts the spatial study phase mean P3 amplitude by group from the 300 to 450 ms time window. The first three positions from the maintenance condition and all seven positions are highlighted for the update condition as these positions were relevant for working memory processing. Error bars represent standard error.

The verbal study phase also showed substantial task effects (see Figure 7). There was a graded effect of condition on P3 amplitude based on the level of attention required, $F(1.70, 178.50) = 90.79$, $p < .0001$, $\eta^2_p = .46$, $\epsilon = .85$. Contrasts ($\alpha_{corrected} = (.05/2) = .025$) revealed that the overall amplitude for the update condition was larger than maintenance amplitude, $F(1, 108) = 102.59$, $p < .0001$, $\eta^2_p = .49$, and maintenance amplitude was larger than control amplitude, $F(1, 108) = 11.37$, $p = .001$, $\eta^2_p = .10$. There was a significant main effect of study position on P3 amplitude, $F(3.96, 415.80) = 21.58$, $p < .0001$, $\eta^2_p = .17$, $\epsilon = .66$. Again, there was a significant interaction of condition by position, $F(8.52, 894.60) = 32.91$, $p < .0001$, $\eta^2_p = .24$, $\epsilon = .71$. This interaction was driven by the maintenance condition, where P3 amplitude increased from position 1 to 2 and then decreased from position 3 to 4, signaling the use of attention to study the first three items and is a similar effect to what was shown in the spatial task. For the verbal study phase, the main effect of age was significant, $F(1, 105) = 8.97$, $p = .0034$, $\eta^2_p = .08$. Older adults had an overall larger P3 amplitude than younger adults (see Figure 7, panel B). There was no main effect of language or interaction with age group, Fs < 1.

A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Potential (μ V)
Time (ms)
Control 1
Control 2
Control 3
Control 4
Control 5
Control 6
Control 7
CPz
Potential (μ V)
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Main 1
Main 2
Main 3
Main 4
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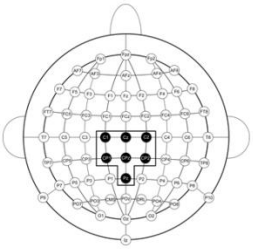
Update 1
Update 2
Update 3
Update 4
Update 5
Update 6
Update 7



B

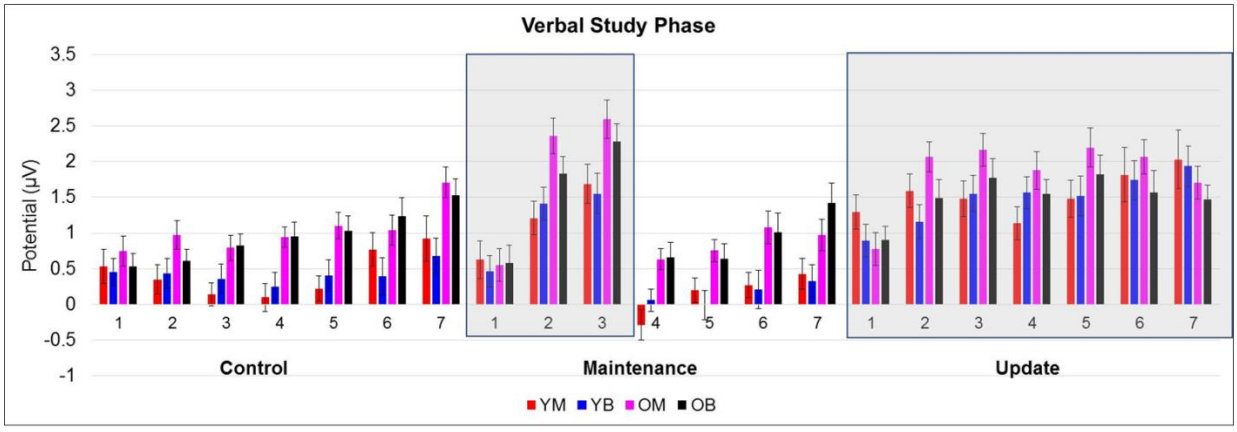

Verbal Study Phase
Potential (μV)
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
1 2 3 4 5 6 7
1 2 3 4 5 6 7
1 2 3 4 5 6 7
Control
Maintenance
Update
YM YB OM OB

Figure 7. Grand averaged waveforms for item serial position 1-7 from the verbal study phase are presented by condition (top- control, middle- maintenance, bottom- update) for the representative electrode, CPz (panel A). The P3 time window of 300 to 450 ms is highlighted by the grey box. The bar graph (panel B) depicts the verbal study phase mean P3 amplitude by group from the 300 to 450 ms time window. The first three positions from the maintenance condition and all seven positions are highlighted for the update condition as these positions were relevant for working memory processing. Error bars represent standard error.

The verbal study phase also elicited significant two-way interactions between condition and age group, $F(1.70, 178.50) = 7.58$, $p = .0013$, $\eta^2_p = .07$, $\epsilon = .85$, and between study position and age group, $F(3.96, 415.80) = 3.84$, $p = .0046$, $\eta^2_p = .04$, $\epsilon = .66$. Furthermore, there was a significant three-way interaction of condition by study position by age, $F(8.52, 894.60) = 2.46$, $p = .0105$, $\eta^2_p = .02$, $\epsilon = .71$. To examine this three-way interaction, a three-way ANOVA was run on condition by study position by age, collapsing across language group. Tukey's multiple comparison tests indicated that older adults had larger amplitude than younger adults for positions 3–7 for the control condition, positions 2–7 for the maintenance condition, and there were no significant age group differences across positions for the update condition (see Figure 7, panel B). There were no other significant group interactions with condition or position in the initial four-way ANOVA, Fs < 1.3.

Summary of Study Phase P3 Results

For the study phase, there were significant task effects for each domain that replicated the effects shown by Watter et al. (2010). For the verbal task, there was an increase in P3 amplitude from control to maintenance to the update condition. For the spatial task, overall amplitude was

similar for the control and maintenance conditions, but there was a substantial increase in amplitude for the update condition. The control condition had stable amplitude across study item positions with a slight increase towards the end of the series. The maintenance condition displayed a marked increase in amplitude for positions two and three, and then decreased dramatically. The update condition showed sustained high amplitude across positions. There were significant effects of age for studying verbal items, but not for studying spatial items. Older adult displayed larger amplitude than younger adults to perform both the verbal control and the maintenance conditions. For the verbal update condition, younger adult amplitude was "ramped up" to a similar activation level as the older adults to perform the most effortful condition. There were no effects or interactions with language group at this stage of working memory processing.

Recognition Mean Amplitude: Frontocentral and Centroparietal P3 (300 to 450 ms)

On each trial immediately after the study phase, participants made a recognition decision to the memory probe. The following results are based on P3 activation time-locked to the memory probe for each domain. For this four-way repeated measures analysis, age group and language group were the between-subjects variables and region of interest (ROI: frontocentral, centroparietal) and condition (control, maintenance, update) were the within-subjects variables. The frontocentral ROI consisted of the average amplitude across six electrodes F1, Fz, F2, FC1, FCz, and FC2. The centroparietal ROI consisted of the average amplitude across seven electrodes C1, Cz, C2, CP1, CPz, CP2, and Pz.

For spatial recognition, younger adults had an overall larger P3 amplitude than older adults, $F(1, 104) = 11.04$, $p = .0012$, $\eta^2_p = .10$ (see Figure 8). There was no main effect of language or interaction with age group, Fs < 1. P3 amplitude varied by ROI, $F(1, 104) = 18.42$, $p < .0001$, $\eta^2_p = .15$, with a larger P3 amplitude for the frontocentral ROI than for the centroparietal

ROI. Condition effects were elicited by the memory probe, $F(1.74, 180.96) = 111.97$, $p < .0001$, $\eta^2_p = .52$, $\epsilon = .87$. Contrasts ($\alpha_{corrected} = (.05/2) = .025$) showed that there was a graded condition effect. Update amplitude was larger than maintenance amplitude, $F(1, 107) = 87.68$, $p < .0001$, $\eta^2_p = .45$, and maintenance amplitude, $F(1, 107) = 39.08$, $p < .0001$, $\eta^2_p = .27$, was larger than control amplitude. There was a significant interaction between ROI and condition, $F(1.92, 199.68) = 34.10$, $p < .0001$, $\eta^2_p = .25$, $\epsilon = .96$. To assess this interaction, contrasts were run for each ROI between adjacent levels of condition ($\alpha_{corrected} = (.05/4) = .0125$). For the frontocentral ROI, there was a significant increase in amplitude between the control and the maintenance condition ($p < .0001$), and between the maintenance and the update condition ($p < .0001$). For the centroparietal ROI, the difference in amplitude between the control and the maintenance condition did not survive the alpha correction ($p = .037$), but there was a significant increase in amplitude between the maintenance and the update condition ($p < .0001$).

Age group interacted with ROI, $F(1, 104) = 40.78$, $p < .0001$, $\eta^2_p = .28$, and with condition, $F(1.74, 180.96) = 6.79$, $p = .0023$, $\eta^2_p = .06$, $\epsilon = .87$. Follow-up two-way ANOVAs were run to compare age groups on average amplitude for each ROI and on average amplitude for each condition, collapsing across language group. For the ROI by age effect, Tukey's multiple comparison tests indicated that younger adults had larger centroparietal amplitude than older adults, whereas both age groups had similar amplitude for the frontocentral ROI (see Figure 8, panel B). For the condition by age effect, Tukey's multiple comparison tests indicated that younger adults had larger amplitude than older adults for the maintenance and update condition, whereas both age groups had similar amplitude for the control condition. There were no other significant group interactions with ROI or condition in the initial four-way ANOVA, Fs < 2.

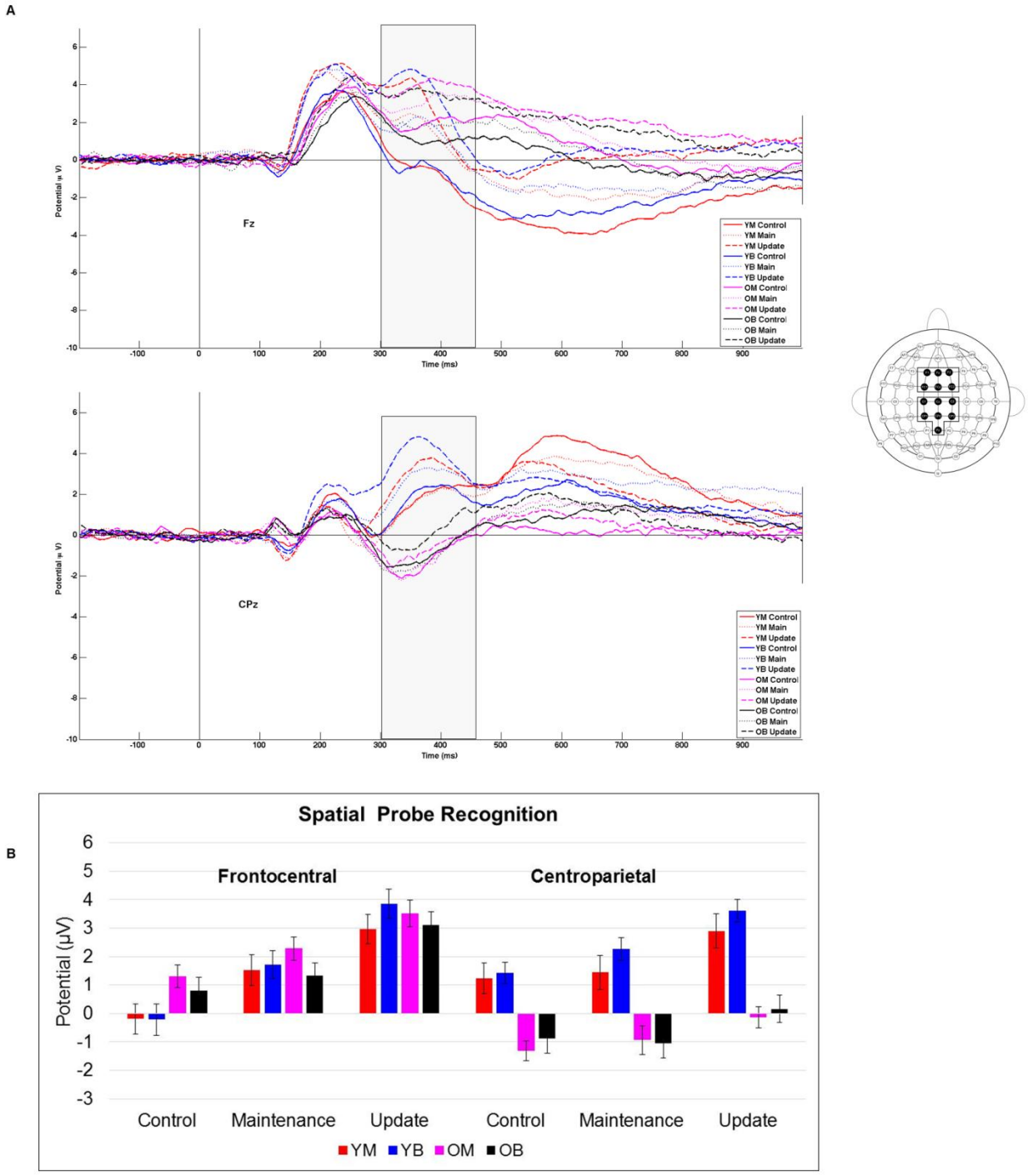


Figure 8. Grand averaged waveforms for spatial recognition are presented by group and condition for the representative electrodes, Fz and CPz (panel A). The bar graph (panel B)

depicts mean P3 amplitude by group from the 300 to 450 ms time window. Error bars represent standard error.

For verbal recognition, there were no significant main effects or interaction of age group and language group, *F*s < 2.9. The main effect of ROI was the opposite to what was shown for the spatial task, $F(1, 105) = 22.80$, $p < .0001$, $\eta^2_p = .18$. P3 amplitude was higher for the centroparietal ROI than for the frontocentral ROI (see Figure 9). The effect of condition showed the same graded pattern as the spatial task, $F(1.64, 172.20) = 144.55$, $p < .0001$, $\eta^2_p = .58$, $\epsilon = .82$. Update amplitude was larger than maintenance amplitude, $F(1, 108) = 127.91$, $p < .0001$, $\eta^2_p = .54$, and maintenance amplitude, $F(1, 108) = 25.81$, $p < .0001$, $\eta^2_p = .19$, was larger than control amplitude (contrast αcorrection = (.05/2) = .025).

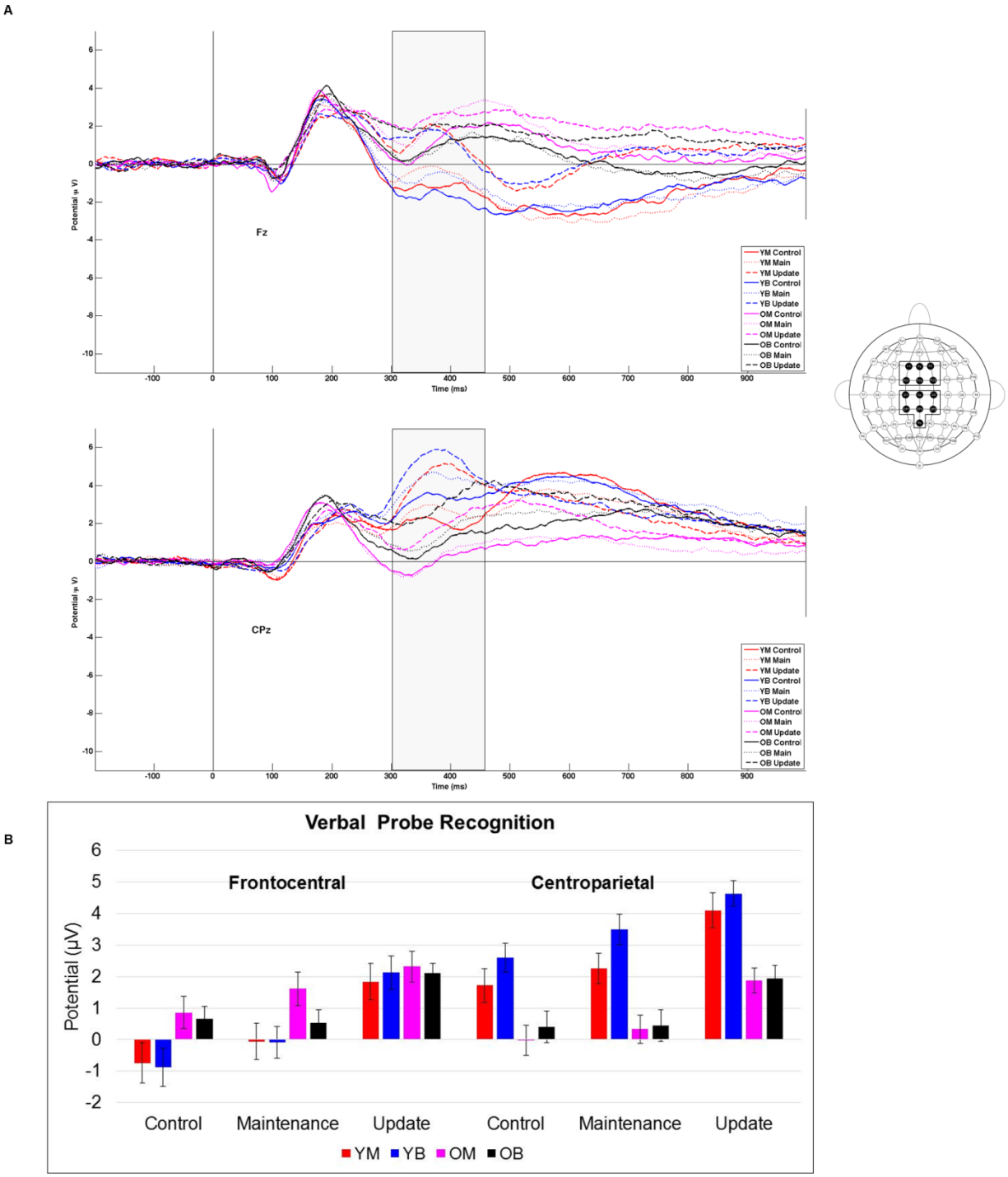


Figure 9. Grand averaged waveforms for verbal recognition are presented by group and condition for the representative electrodes, Fz and CPz (panel A). The bar graph (panel B)

depicts mean P3 amplitude by group from the 300 to 450 ms time window. Error bars represent standard error.

Verbal recognition produced two significant interactions between age and ROI, $F(1, 105) = 48.36$, $p < .0001$, $\eta^2_p = .32$, and age and condition, $F(1.64, 172.20) = 6.64$, $p = .0033$, $\eta^2_p = .06$, $\epsilon = .82$, and three-way interactions of ROI by condition by age, $F(1.74, 182.70) = 4.12$, $p = .0226$, $\eta^2_p = .04$, $\epsilon = .87$ and ROI by condition by language, $F(1.74, 182.70) = 3.50$, $p = .0387$, $\eta^2_p = .03$, $\epsilon = .87$ (see Figure 9, panel B). To clarify the three-way interactions, follow-up three-way ANOVAs were run collapsing across either age or language group. For the ROI by condition by age effect, Tukey's multiple comparison tests indicated that for the frontocentral ROI older adults had larger amplitude than younger adults for the control and maintenance condition, whereas for the update condition, younger adults ramped up recognition amplitude to the level seen in older adults. For the centroparietal ROI, younger adults have larger amplitude than older adults across all three conditions (see Figure 9, panel B).

For the ROI by condition by language effect, Tukey's multiple comparison tests indicated that there were no language group differences across conditions and ROIs. Therefore, contrasts were run for each language group for each ROI between adjacent levels of condition ($\alpha_{corrected} = (.05/8) = .00625$) (see Figure 10). For the bilingual group across the frontocentral ROI, the maintenance condition did not differ from the control condition ($p = .09$), but the update condition was significantly larger than the maintenance condition ($p < .0001$). For the centroparietal ROI, the difference between the maintenance and control condition did not survive alpha correction ($p = .0085$), but the update condition was significantly larger than the maintenance condition ($p < .0001$). For the monolingual group across the frontocentral ROI, the

maintenance condition was significantly different from the control condition ($p = .0002$), and update condition was significantly larger than the maintenance condition ($p < .0001$). For the centroparietal ROI, the same pattern was shown as the maintenance condition was significantly different from the control condition ($p = .0011$), and update condition was significantly larger than the maintenance condition ($p < .0001$).

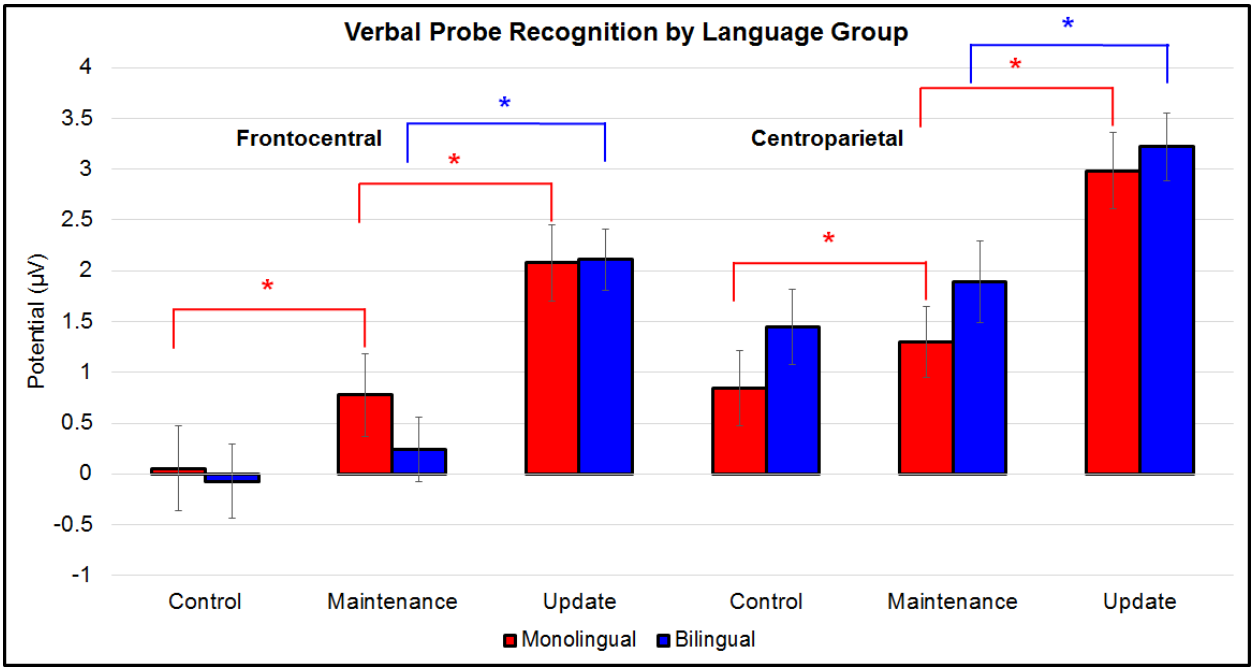


Figure 10. Verbal probe recognition P3 amplitude by language group. Error bars represent standard error. Asterisks for condition contrasts are significant at $p < .00625$.

Summary of Probe Recognition P3 Results

Significant task effects were present for each domain, and there was an increase in amplitude from control to maintenance to the update condition. For spatial recognition, younger adults had larger centroparietal P3 amplitude than older adults but both age groups had similar levels of amplitude in frontocentral regions. Younger adults had larger P3 amplitude than older

adults for the two memory conditions (i.e., maintenance and update), but not for the control condition. For verbal recognition, younger adults had larger centroparietal P3 amplitude than older adults across all conditions. Older adults had larger frontocentral P3 amplitude than younger adults for the control and maintenance condition, however younger adults "ramped up" P3 amplitude to a similar activation level as older adults for the update condition. A language group interaction emerged for verbal recognition. Monolinguals displayed a graded effect of condition on P3 amplitude, whereas the bilinguals showed a similar activation level for the control and maintenance condition but showed a significant increase in amplitude for the update condition. See Table 9 for a full summary of the group effects found for P3 amplitude for both the study phase and probe recognition.

Table 9.

Summary of P3 Amplitude Results by Group Effects

Memory Process	Domain	Age Effect	Language Effect
Study	Spatial	Y < O (p = .07)	ns
Study	Verbal	Y < O for control and maintenance, not update	ns
Recognition	Spatial	O < Y for centroparietal, not frontocentral O < Y for maintenance and update, not control	ns
Recognition	Verbal	Y < O for frontocentral control and maintenance, not update O < Y for centroparietal control, maintenance, and update	control = maintenance < update for bilinguals control < maintenance < update for monolinguals

Discussion

This is the first study to examine the neural correlates associated with performance in a running memory procedure in younger and older bilinguals and monolinguals using verbal and nonverbal stimuli. Groups were matched on relevant background measures, with the exception of English vocabulary knowledge. The pattern of higher vocabulary in older than younger adults and in monolinguals than bilinguals is a typical finding in the literature (e.g., Luo et al., 2013) and replicates the results seen in Chapter 2. For working memory performance, expected age-related declines were shown with lower accuracy and slower RT for older adults than younger adults. The graded condition effects from Watter et al. (2010) were replicated, with more effortful conditions producing lower accuracy and slower RT. In terms of accuracy, older adults had great difficulty with the spatial update condition, supporting prior findings that older adults perform more poorly for spatial working memory than verbal (Hale et al., 2011; Luo et al., 2013). For RT, older adults were especially slower than younger adults for the update condition, which required the highest level of attentional control. Aging also showed a larger impact on the control condition in the verbal version, possibly because of differences in speed of processing.

During the study phase, the centroparietal P3 task results replicated Watter et al. (2010). For verbal working memory, the condition effect on P3 amplitude was graded in the predicted direction with greater amplitude for more demanding conditions (i.e., control < maintenance < update), whereas similar amplitude was shown for maintenance and control in the spatial task but increased for the update condition. The serial position effect during the study phase in the maintenance condition was similar across domains, and P3 amplitude significantly increased across positions 2 and 3 from 1 for holding the first three items in memory, and then significantly decreased. In terms of the effects of aging during the study phase, significant results were shown

for the verbal task but not the spatial task. Older adults had larger P3 mean amplitude than younger adults for studying the verbal items but this effect was marginal in the spatial task. The interaction effect with aging while studying verbal items indicated that older adults had higher amplitude than younger adults for the control and maintenance conditions, but not for the update condition. This suggests that younger adults display a pattern of neural efficiency at the study phase, increasing the P3 to extent seen in older adults only when the attentional demands are high. Likewise, the higher P3 for older adults than younger adults suggests that for certain task conditions greater attentional control is required to study items. An alternative explanation is that older adults may be distracted by/processing irrelevant items in the control and maintenance study series more than younger adults, resulting in a larger P3. In Watter et al. (2010) spatial amplitude was lower than verbal amplitude during the study phase, therefore either the spatial task does not elicit a P3 that is powerful enough to assess group effects or due to the inherent difficulty of the spatial task with aging, older adults are unable to elicit a larger P3 than younger adults to deal with the attentional demands during the study phase. No language group differences were shown at the study phase.

For the P3 elicited during recognition, frontal regions were analyzed along with the centroparietal ROI. During spatial recognition, effects varied by region. Greater P3 amplitude was shown in the frontocentral ROI than the centroparietal ROI, indicating that more frontal resources were needed. Younger and older adults displayed similar overall amplitude in the frontal ROI, but younger adults had a larger centroparietal P3 that is in line with the working memory and aging parietal findings during recognition (Fjell, Walhovd, & Reinvang, 2005; McEvoy, Pellouchoud, Smith, & Gevins, 2001; Müller & Knight, 2002; Saliasi, Geerligs, Lorist, & Maurits, 2013). A graded condition effect was shown that was similar to the study phase, with

more effortful conditions requiring a larger P3 (i.e., control < maintenance < update). An age by condition interaction demonstrated that younger adults had a larger P3 than older adults during recognition for the two memory conditions, but not for the control condition. No language group differences were found for spatial recognition.

For verbal recognition, the graded condition effect was also shown, with more effortful conditions requiring a larger P3. However, the ROI effect that was seen with spatial recognition reversed and larger overall amplitude was present in the centroparietal ROI than in the frontocentral ROI. Along with this reversal, significant group interactions were present with ROI and condition. The interaction with age demonstrated that for the frontal ROI, older adults had larger amplitude than younger adults for the control and maintenance condition but not for the update condition, whereas for the centroparietal ROI younger adults had larger amplitude for all three conditions paralleling the spatial recognition results. A language group interaction emerged, indicating that monolinguals displayed the graded condition effect in both the frontal and posterior ROI whereas bilinguals displayed a pattern across ROIs whereby control and maintenance had similar amplitudes but amplitude increased significantly for the update condition.

These complex results are consistent with the patterns predicted by two major theories of brain functional reorganization patterns in aging. During the study phase, older adults required greater activation than younger adults to process verbal stimuli during the less effortful conditions, whereas younger adults elicited a P3 to this level of activation only for the update condition. Although marginal (p = .07), older adults also required more activation than younger adults to study spatial stimuli. This pattern resembles the CRUNCH model of aging (Reuter-Lorenz, & Cappell, 2008). In this model, older adults attempt to utilize greater activation to

perform cognitive tasks at the same level of younger adults, although in the current study older adult accuracy was lower than younger adults, but still reached a reasonable level of performance. In addition, during verbal recognition in working memory, older adults required more frontal resources than younger adults, whereas both groups showed frontal activation during the more difficult spatial recognition task. Greater recruitment of frontal regions with aging supports the PASA model (Davis, Dennis, Daselaar, Fleck, & Cabeza, 2008), and older adults showed significantly lower activation in centroparietal regions during recognition across domains, a difference that likely contributed to poorer memory performance with aging.

The pattern of results seen for verbal recognition in bilinguals in which P3 activation only increased when greater attentional control was required may be indicative of a more efficient processing strategy in bilinguals. An overall larger P3 in bilinguals than monolinguals was not shown statistically, although visually this pattern is seen in particular for the younger bilinguals more posteriorly in Figures 8 and 9 during recognition processing. Therefore, a larger bilingual than monolingual P3 may be more likely realized for memory tasks that involve greater interference processing in memory or much higher levels of attentional control. Alternatively, greater analysis power may be seen through use of the multivariate method of partial least squares analysis (PLS) in which varying network patterns of brain activation across age and language groups can be examined across memory conditions at the whole brain level. This approach was utilized in Chapter 4 using the memory recognition data from the current study, as more extensive age and language group effects were shown at the neural level during the decision stage of memory processing.

Chapter 4. Neural Networks Underlying Working Memory Processing Vary with Aging and Bilingualism

Research examining the neural correlates of memory processing between language groups is still in its early stages. Preliminary work from Chapter 3 using event-related potentials (ERPs) has shown some evidence of language group differences during recognition, however the generalizability of these results may be limited for two reasons. First, language group processing differences may be more likely to be seen at the whole brain level as opposed to more focal regions of interest (ROIs). Second, an examination of signal variability as opposed to mean signal, where effects may be diminished, may provide additional information of where group neural differences may arise. The goal of the current study was to address these two issues by analyzing the working memory ERP data from Chapter 3 using the multivariate analysis approach of partial least squares (PLS, Krishnan, Williams, McIntosh, & Abdi, 2011; McIntosh, Bookstein, Haxby, & Grady, 1996; McIntosh, Chau, & Protzner, 2004) to examine relevant network patterns. Both EEG amplitude and EEG multiscale entropy (MSE, Heisz & McIntosh, 2013), which is a measure of signal variability, were examined across age and language groups. These methods of analysis will allow greater insight into the neural mechanisms of how aging and bilingualism impact attentional control in working memory.

Evidence is accumulating that the experience of lifelong bilingualism results in functional modifications at the whole brain level. PLS analysis (see methods section for a detailed description) has been used with resting-state (i.e., absence of a cognitive task) fMRI data to assess how intrinsic brain network patterns differ by language group. For example, Luk, Bialystok, Craik, and Grady (2011) demonstrated that at rest, older adult bilinguals showed long-range patterns of functional activity with frontal-parietal and frontal-occipital connections,

whereas older monolinguals had a pattern that was more localized to the frontal lobes/anterior regions. In a separate study with older adults, bilinguals showed stronger resting-state connectivity than monolinguals in the default mode network and the frontoparietal control network (Grady, Luk, Craik, & Bialystok, 2015). The default mode network plays a role in memory processing and shows substantial declines in connectivity with aging (Andrews-Hanna et al., 2007; Buckner, Andrews-Hanna, & Schacter, 2008). The frontoparietal control network allows for flexible switching between the default mode network and the dorsal attention network, to engage internally- versus externally-directed cognition, and this opposing functional relationship also shows declines with aging (Spreng, Stevens, Viviano, & Schacter, 2016).

Similar fMRI findings have been found using younger adult bilinguals. Xue, Dong, Jin, and Chen (2004) had unbalanced Chinese-English young adult bilinguals perform verbal 2-back working memory tasks in both their L1 and L2. An overlapping, left dominant frontal-parietal network was shown to underlie working memory processing for both L1 and L2, although certain regions of the network were activated more for processing in L2 and L2 tasks were associated with more errors. These results provide evidence that large-scale brain network changes are seen with lifelong bilingualism involving regions relevant for working memory processing (Baldo & Dronkers, 2006; Eriksson, Vogel, Lansner, Bergström & Nyberg, 2015) and regions known to decline with aging (Peters, 2006).

Several researchers have proposed that while monolinguals begin to rely more on frontal lobe activity with aging, older bilinguals utilize increased frontal-parietal/anterior-posterior connections (Grant et al., 2014; Grundy et al., 2017a). Work with EEG oscillatory networks and cognitive control in younger adults has also demonstrated that high versus low capacity working memory individuals show differences along a fronto-parietal network in terms of post-conflict

adaptation, indicating possible bidirectionality of this network for attention and memory processing (Gulbinaite, van Rijn, & Cohen, 2014). Additional work with younger adults has shown increased EEG synchronization between anterior and posterior regions and between hemispheres occurs for successful recall of words relative to non-recalled words (Weiss & Rappelsberger, 2000).

Although there are no studies directly comparing memory task networks across younger and older adult bilinguals and monolinguals, an fMRI study by Gold, Kim, Johnson, Kryscio, and Smith (2013) using a cognitive control task may be informative. Participants performed single blocks of a colour or shape decision task and a switch block in which both tasks were intermixed. At the behavioural level, older adults had a higher proportional cost on RTs than younger adults due to switching but there was also evidence of a smaller switch cost in the older bilinguals than the older monolinguals. Based on a neural switch cost, older adult bilinguals were shown to have less activity than older monolinguals in three frontal regions: the left dorsolateral prefrontal cortex, left ventrolateral prefrontal cortex, and the anterior cingulate cortex. Thus, for more effortful task costs, the older bilinguals displayed a neural pattern that was similar to younger adults.

In a similar vein, work with aging and ERP using an oddball paradigm (i.e., responding to a rare target stimulus) designed to elicit a P3 component has shown that within an older adult sample, those participants who had a more frontally-oriented P3 maximum had poorer performance on frontally-oriented neuropsychological tests than older adults who had a more parietally-oriented P3 maximum that resembled younger adults (Fabiani, Friedman, & Cheng, 1998). The older adults who displayed a parietal P3 maximum, however, were similar to the older adults who displayed a frontal P3 maximum in terms of overall P3 amplitude and more

centralized activity, and still showed lower performance than younger adults on some of the neuropsychological measures. Later work by Duarte, Ranganath, Trujillo, and Knight (2006) using a remember/know paradigm to assess more controlled than automatic aspects of recognition memory also demonstrated that older adults that performed equivalently to the younger adults had the same scalp ERP topography as the younger adults, whereas poorer performing older adults had a divergent pattern of activity across the scalp. Thus, across these two studies, there were performance benefits for older adults who had a neural pattern that resembled younger adults relative to older adults who did not resemble younger adults.

The use of multiscale entropy (MSE) analysis can provide information pertaining to the complexity of the EEG signal within neural networks, and is important for understanding the underlying mechanisms behind group differences in working memory processing. MSE analyses are based on the variance within the signal at multiple timescales. By condensing the signal through a procedure known as down-sampling (e.g., averaging two or more consecutive data points in the signal) and taking a ratio of how often preset amplitude patterns occur at each timescale, mathematically, one can assess the predictability and variability of the event-locked amplitudes within the signal separate from any variation due to noise (Heisz, Shedden, & McIntosh, 2012; see method section for further details). A more variable neural signal is representative of greater information processing and integration and is typically associated with better cognitive function. Takahashi and colleagues (2009) have shown that following photic stimulation, in which participants are exposed to white flickers of light at varying frequencies, younger adults showed a more dynamic EEG response than older adults to this type of basic perceptual stimulation (see also, Grady & Garrett, 2014 for evidence of lower signal variability in older adults than younger adults using fMRI).

More relevant to the current study, Heisz, Gould, and McIntosh (2015) examined MSE in relation to aging, experience with being physically active, and performance on a directed forgetting working memory paradigm. In this task, participants are required to remember all of the presented digits, and then, following a retention interval, they may be asked to either still remember all of the numbers or only half of the numbers based on their presentation colour for a second retention interval. At recognition, participants had to indicate if the probe contained numbers they were instructed to remember. On certain trials, the probe contained previously studied numbers that they were instructed to forget. This process of updating working memory to forget previously studied items requires effortful control. The MSE analysis that was conducted for the remember-half trials revealed a change in network dynamics with aging. Overall, older adults showed more local processing than younger adults with greater sample entropy at a finer timescale (1–10 ms), whereas younger adults showed more distributed processing than older adults with greater complexity at coarser timescales (15–20 ms). For older adults, a negative correlation was present between entropy at fine and coarse timescales, but younger adults showed no relationship between entropy at fine and coarse timescales. In addition, increased physical activity was associated with better performance in older adults but in not younger adults. Based on the results of a mediation analysis in the older adult sample, greater physical activity was related to more local processing and less distributed processing leading to better performance on the directed forgetting working memory paradigm, and may reflect a type of experience-based neuroplasticity seen with aging.

For work with bilingualism, there is one study that has looked at EEG MSE in younger adult bilinguals and monolinguals using a perceptual task-switching paradigm, known as the bivalency task (Grundy, Anderson, & Bialystok, 2017b). Bilinguals were shown to have greater

MSE than monolinguals more posteriorly at coarse time scales, localized to the electrodes in the occipital lobe. Greater occipital MSE was linked to faster performance in bilinguals and slower performance in monolinguals. When the relationship between MSE for the occipital electrode, Oz, and frontal electrode Fz was examined in terms of trial type, further language group differences emerged. For univalent trials, where participants needed to make a decision pertaining to one perceptual feature (i.e., shape colour, number odd or evenness, or letter case) that occurred in a mixed block with conflict trials, both groups showed a negative correlation where faster RT was associated with greater occipital-frontal coupling. For the bivalent/conflict trials in which a decision needed to be made based on one perceptual feature but the stimulus also contained an irrelevant feature (i.e., a coloured letter), monolinguals still had a negative correlation between RTs and occipital-frontal coupling but bilinguals now showed a positive correlation. These results indicate that bilinguals tend to rely on increased signal variability localized to the posterior regions to deal with perceptual conflict whereas monolinguals also require frontal resources. How patterns of MSE relate to memory performance in older and younger adult bilinguals has yet to be considered.

In the current investigation, the memory recognition EEG data from Chapter 3 were analyzed using PLS, with (1) EEG amplitude and (2) EEG MSE as the measures. The P3 amplitude analysis from Chapter 3 displayed some evidence of language group effects at recognition, and it was therefore hypothesized that PLS will provide insight into the neural network patterns that differentiate younger and older adult bilinguals from their monolingual counterparts. It was predicted that bilinguals will show a pattern of activity and signal entropy that relied more on posterior regions than found for monolinguals, and that monolinguals, particularly into older age, will rely more on frontal regions than bilinguals as the level of

attentional control required for the task increases (i.e., control condition < maintenance < update). In line with the functional work by Gold et al. (2013), it was predicted that older adult bilinguals will resemble younger adults in terms of switching between networks and activation levels (amplitude) and brain states (MSE) across working memory conditions. Finally, it was predicted that verbal tasks will elicit a more left-lateralized pattern of activity than spatial tasks (Kiss et al., 2007; Watter et al., 2010), and that older adults (Cabeza, 2002) will display a more bilateral pattern of activity than younger adults.

Method

Mean-centered PLS analysis, a multivariate technique that is similar to principle components analysis (PCA) (see Krishnan, Williams, McIntosh, & Abdi, 2011; McIntosh, Bookstein, Haxby, & Grady, 1996; McIntosh, Chau, & Protzner, 2004, for detailed tutorials and descriptions of PLS analysis) was performed on the electrophysiological recognition data from Chapter 3. Mean-centered PLS allows for an examination of how distinct patterns of neural activity relate to task conditions and group membership. For the current study, the relationships between (a) EEG amplitude, working memory task condition (control, maintenance, update), and group (young monolingual, young bilingual, old monolingual, old bilingual), and (b) EEG MSE values, working memory task condition (control, maintenance, update), and group (young monolingual, young bilingual, old monolingual, old bilingual), were analyzed using PLS.

In mean-centered task PLS, a matrix of group condition averages is computed from brain and design submatrices (i.e., for each group, across participants there are three stacked brain submatrices: one for the control, maintenance, and update condition that stores the EEG data pertaining to that condition). Each data point in this derived matrix is then mean-centered across groups. A procedure known as singular value decomposition is performed on the mean-centered

matrix. Singular value decomposition allows for the maximum covariance between the brain and condition/design measures to be assessed, and outputs three matrices. Two of the matrices represent orthogonal singular vectors for the brain and design variables, also known as the brain and design saliences, and the third matrix contains the singular values. Latent variables (LVs) correspond to the maximum covariance between the projection of the original brain and design values onto their respective salience vectors. The brain saliences are associated with distinct neural patterns that underlie the effects shown for the corresponding LV. Brain saliences can be positive or negative in valence and correspond to the specific pattern loading. Scalp scores represent the summed projection of individual brain data onto brain saliences. When averaged over group, this value represents how strongly each group loads onto the salience pattern per condition.

Permutation testing allows for the significance of a latent variable to be assessed, whereas the reliability is calculated from a bootstrap estimation procedure of the standard errors for the brain saliences. To perform permutation testing, the rows of the brain data matrix are first rearranged without any replacements. Next, the process of singular value decomposition that was described above is performed a larger number of times, for example 1000. The resulting *p*-value is derived from how often the permutated singular values are greater than the original calculated singular values. In contrast, for the bootstrap estimation procedure, sampling with replacement is performed across the brain and the design matrices, and the PLS analysis is rerun *n* times to obtain a standard error for the brain saliences from the bootstrapped samples. The original brain saliences are divided by the standard error computed from the bootstrapped samples, giving the bootstrap ratio (BSR). For BSR ≥ 2, the effect is considered reliable as it is similar to a 95% confidence level for a *Z* score (Grady, McIntosh, Horwitz, & Rapoport, 2000; Krishnan et al.,

2011; McIntosh, Chau, & Protzner, 2004). Saliences are calculated in a single step, therefore there is no need to correct for multiple comparisons (McIntosh, Chau, & Protzner, 2004). The confidence intervals (CIs) presented in the bar graphs for the group scalp scores per condition are also calculated from the bootstrapped samples.

Amplitude PLS analyses were performed using the MATLAB-based PLS toolbox (retrieved from: http://pls.rotman-baycrest.on.ca/source/). The input consisted of the exported preprocessed ERP text files. Separate mean-centered PLS analyses were run for spatial recognition amplitude and for verbal recognition amplitude, using the following parameters: 1000 permutations computed with the bootstrap estimation procedure carried out 200 times.

MSE PLS analyses were performed using a custom MATLAB-based script (derived from Heisz & McIntosh, 2013). Prior to running the PLS analysis, MSE values were calculated from the exported preprocessed ERP text files. The calculation of MSE as a signal complexity measure can be described in two steps (refer to Heisz & McIntosh, 2013, for an in-depth tutorial of MSE calculation procedures). First, sample entropy is calculated by taking a logarithmic ratio of how often predefined data point patterns occur along the EEG time series. The numerator is based on the summed total of how often a number of sequential data point patterns, *m*, occurs. The denominator is the summed total of how often $m + 1$ data point patterns occurs. For example, if $m = 2$, a summed total would be obtained for all repeated two-data point patterns in relation to the summed total for all repeated three-data point patterns ($m + 1 = 3$). For successive data points to be considered part of a pattern, they must fall within a pre-set amplitude threshold range (r). For example, if $r = 0.5$, for subsequent data points to be considered part of the same pattern the difference in their absolute amplitude must be $\leq 50\%$ of the time series standard deviation (Heisz, Gould, & McIntosh, 2015).

Second, to calculate sample entropy measure across multiple time scales, down-sampling is performed (Heisz & McIntosh, 2013). The original time series data is defined as time scale = 1. In the case of time scale = 2, the first two successive data points are averaged together to create the first new point in the new time series (i.e., finer-grained averaging). This averaging procedure is repeated over the course of the entire time series without overlapping neighbouring data points. In the case of time scale = 20, the first twenty successive data points are averaged together to create the first new data point in the time series (i.e., coarser-grained averaging). To convert this scaling method back into ms, the time scale is divided by the EEG system sampling rate (512 Hz) and is multiplied by 1000. For time scale = 1, this results in a digitization rate of 1.953 ms, meaning that a data point occurs approximately every 1.953 ms in the time series. For time scale = 20, based on this calculation a data point has a temporal resolution of approximately 39.063 ms across the time series.

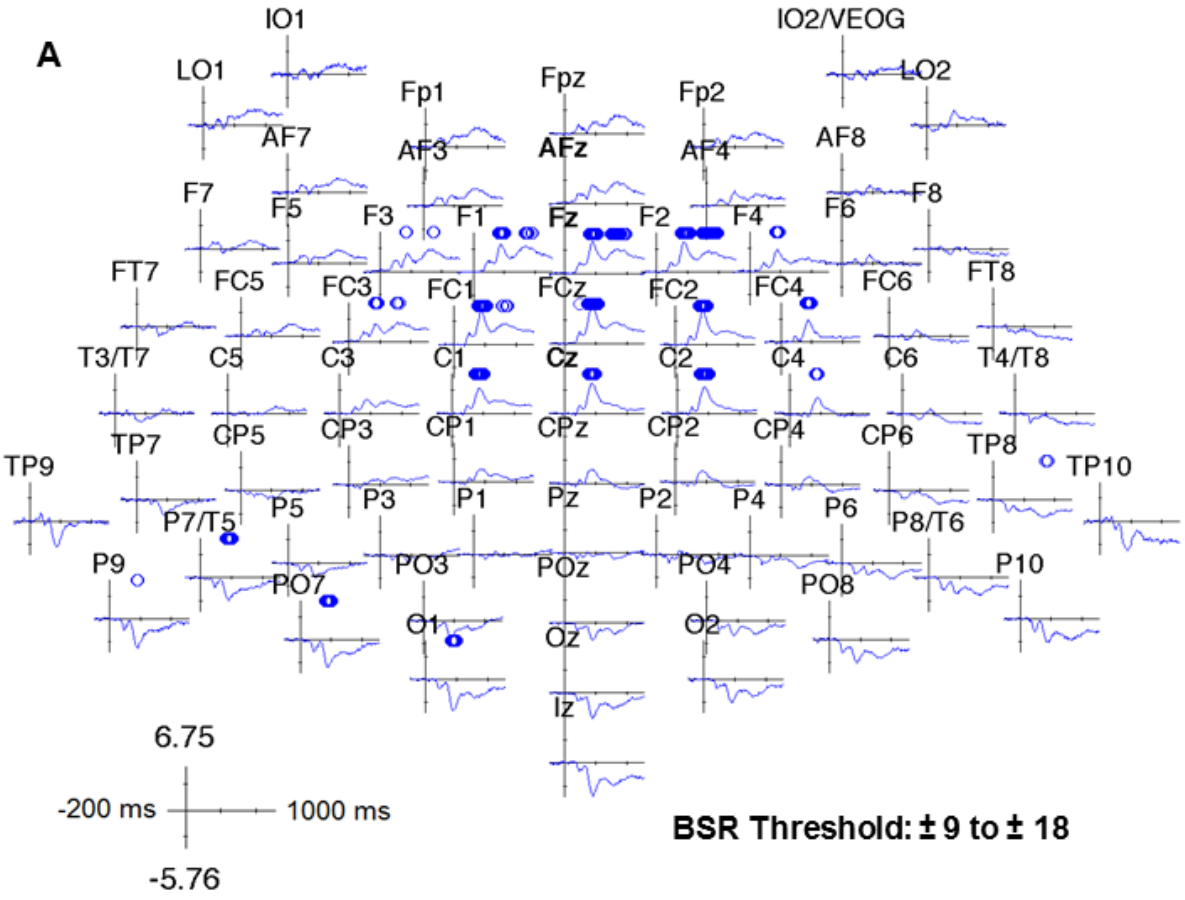
In the current study, MSE calculations were made for each electrode (excluding the six facial electrodes) using the following parameters: $m = 2$, $r = 0.5$, and timescales from 1 to 20, to correspond to previous bilingualism and aging research (Grundy, Anderson, & Bialystok, 2017b for bilingualism; Heisz, Gould, & McIntosh, 2015 for aging). Separate mean-centered PLS analyses were run for spatial recognition MSE and for verbal recognition MSE, using the following parameters: 1000 permutations computed with the bootstrap estimation procedure carried out 200 times.

Results

Amplitude PLS Results for Probe Recognition

LV1 ($p < .001$, 69.8% covariance explained) for spatial amplitude is presented in Figure 11 and represents an effect of task. Salience waveforms are plotted by electrode in panel A and

circles indicate reliable BSRs over the epoch time course in terms of the set thresholds. Positive salience patterns appear above the x-axis and negative salience patterns appear below the x-axis. Panel B presents a bar graph of the average scalp score by group for each condition, plotted with bootstrapped confidence intervals for error bars. Across groups, there is an increase in the scalp scores when moving from the least (i.e., control) to the most effortful condition (i.e., update) (see panel B). The update condition is associated with positive BSR values and relates to activity in a frontocentral ROI occurring around 300–400 ms and later in the time series for the frontal electrodes. In contrast, the control condition is associated with negative BSR values and relates to a pattern of activity that is left-lateralized and occurs in parietal-occipital electrodes (see panel A).


A
IO1
IO2/VEOG
LO1
LO2
Fp1
Fpz
Fp2
AF7
AF3
AFz
AF4
AF8
F7
F5
F3
F1
Fz
F2
F4
F6
F8
FT7
FC5
FC3
FC1
FCz
FC2
FC4
FC6
FT8
T3/T7
C5
C3
C1
Cz
C2
C4
C6
T4/T8
TP7
CP5
CP3
CP1
CPz
CP2
CP4
CP6
TP8
TP9
TP10
P7/T5
P5
P3
P1
Pz
P2
P4
P6
P8/T6
P9
PO7
PO3
POz
PO4
PO8
P10
O1
Oz
O2
Iz
6.75
-200 ms
1000 ms
-5.76
BSR Threshold: ± 9 to ± 18

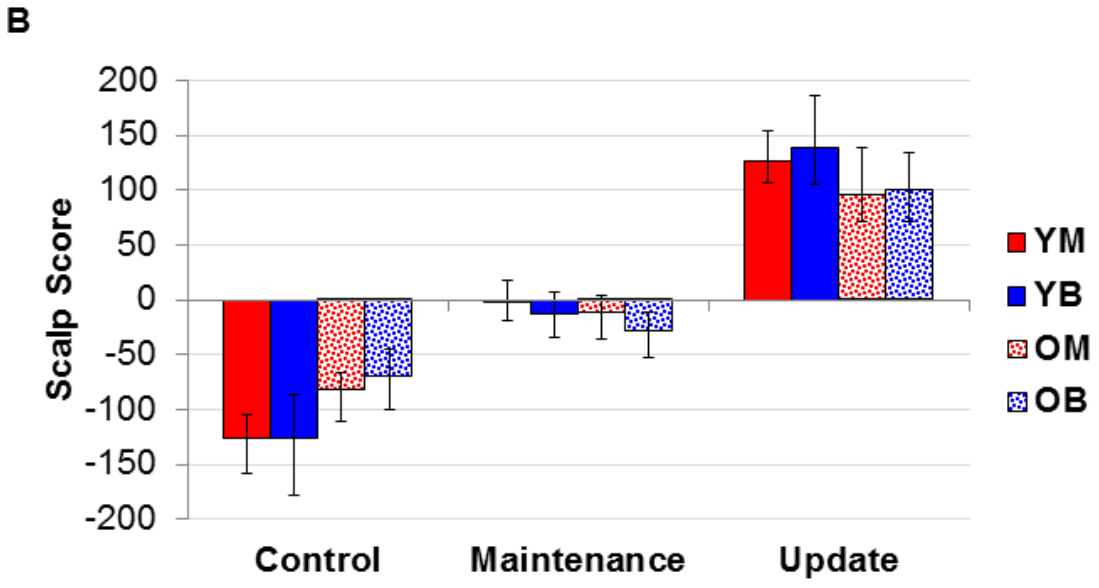
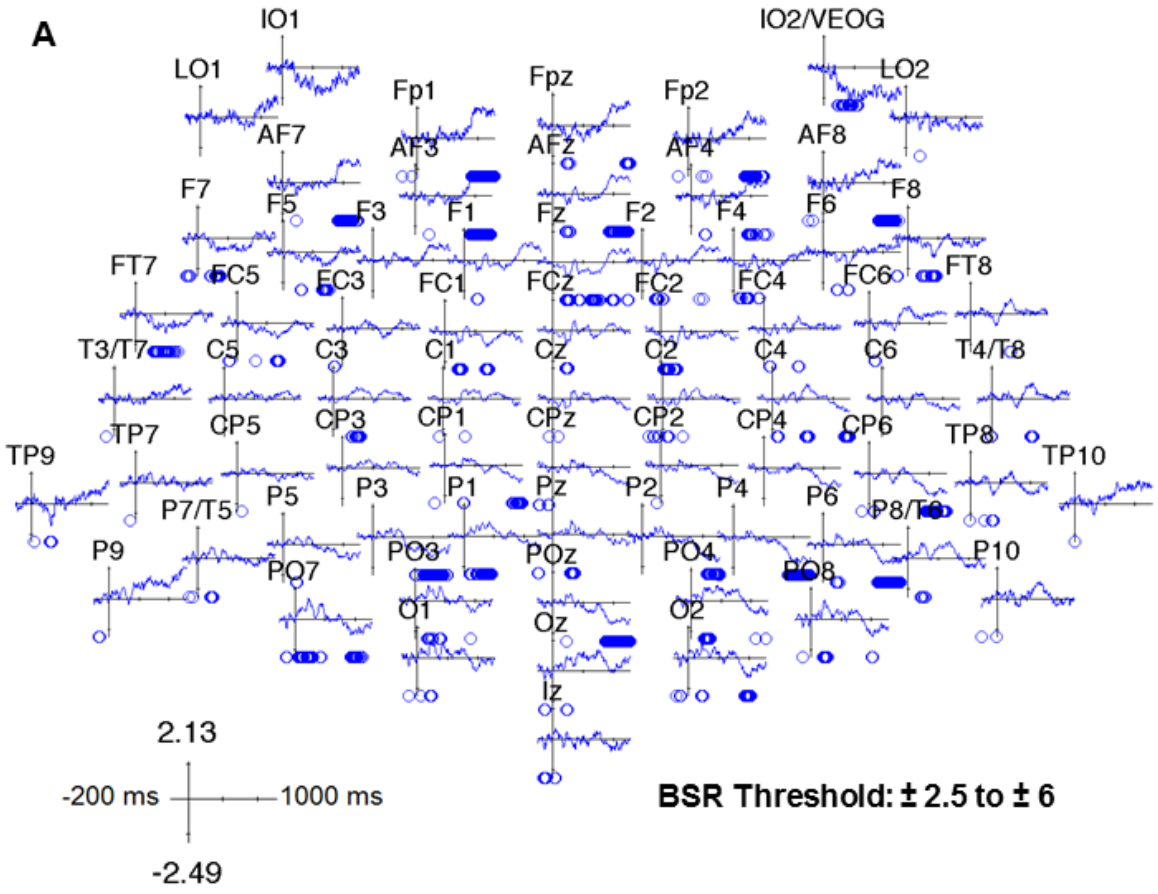

B
Scalp Score
200
150
100
50
0
-50
-100
-150
-200
Control
Maintenance
Update
YM
YB
OM
OB

Figure 11. PLS results for LV1 for spatial amplitude. Salience waveforms are plotted by electrode in panel A with reliable BSRs indicated. Panel B presents a bar graph of the average scalp score by group for each condition. Error bars represent bootstrapped confidence intervals.

LV2 (p = .009, 8.6% covariance explained) for spatial amplitude is presented in Figure 12 and represents an age by language interaction. As shown in panel A, positive BSR values are associated with an amplitude pattern that occurs in frontal regions during a later time window. Negative BSR values are associated with an amplitude pattern that occurs in frontal regions during an earlier time window and in parietal-occipital regions during a later time window. Irrespective of age group, bilinguals display the same pattern across the maintenance and the update conditions, whereas older monolinguals ramp up activation patterns over younger monolinguals (see panel B). There are no differences across groups for the control condition. The pattern of results shown across conditions indicates that older bilinguals resemble young adults in terms of switching between networks and activation levels across working memory conditions.


A
IO1
IO2/VEOG
LO1
LO2
Fp1
Fpz
Fp2
AF7
AF3
AFz
AF4
AF8
F7
F5
F3
F1
Fz
F2
F4
F6
F8
FT7
FC5
FC3
FC1
FCz
FC2
FC4
FC6
FT8
T3/T7
C5
C3
C1
Cz
C2
C4
C6
T4/T8
TP9
TP7
CP5
CP3
CP1
CPz
CP2
CP4
CP6
TP8
TP10
P7/T5
P5
P3
P1
Pz
P2
P4
P6
P8/T6
P9
PO7
PO3
POz
PO4
PO8
P10
O1
Oz
O2
Iz
2.13
-200 ms
1000 ms
-2.49
BSR Threshold: ± 2.5 to ± 6

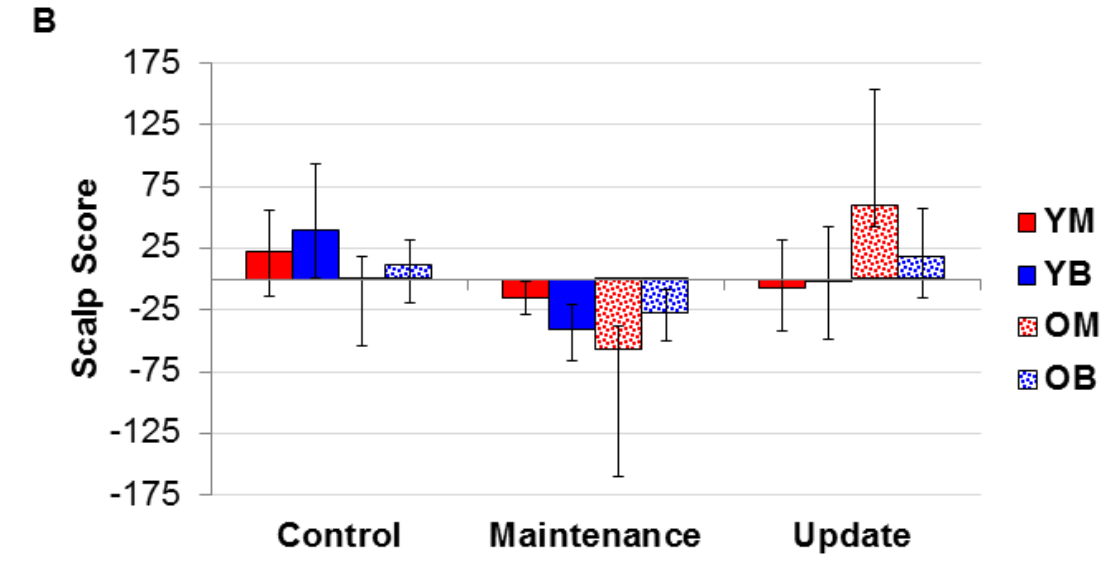
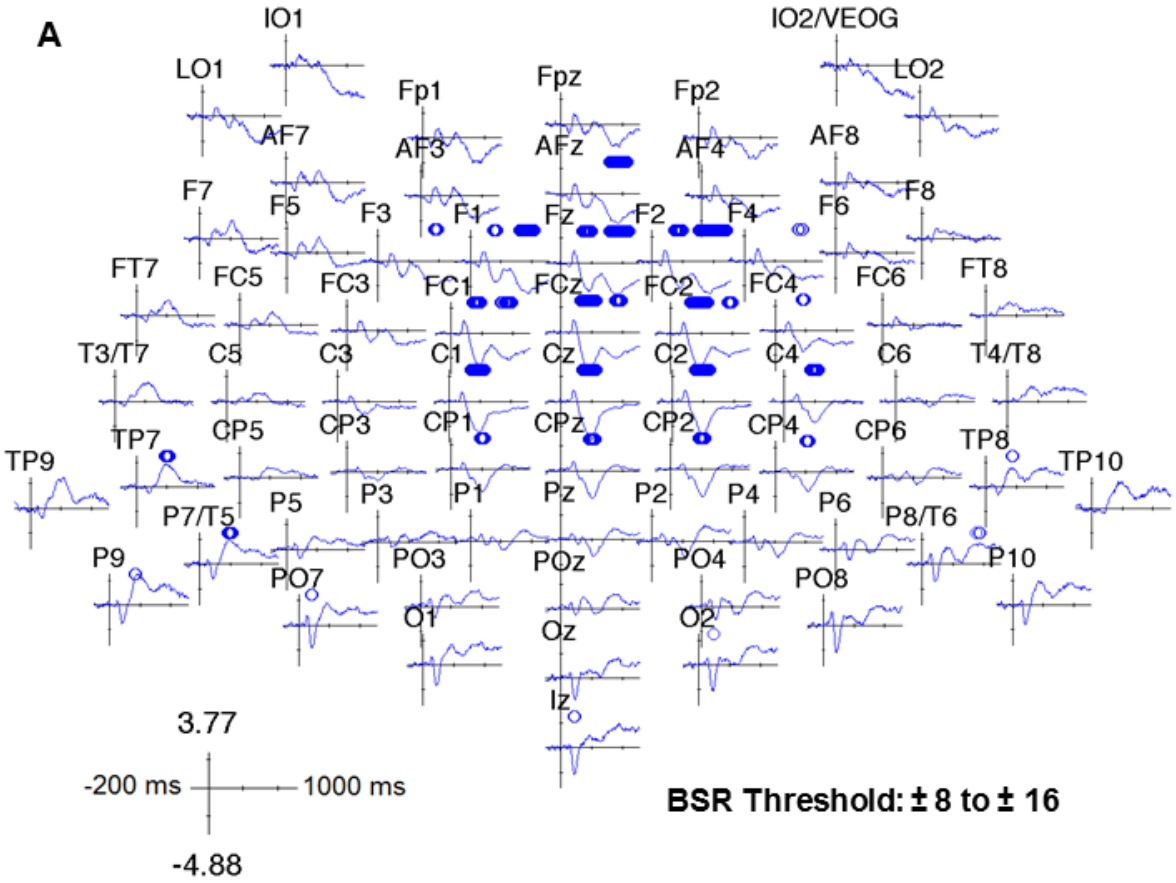

B
175
125
75
25
-25
-75
-125
-175
Scalp Score
Control
Maintenance
Update
YM
YB
OM
OB

Figure 12. PLS results for LV2 for spatial amplitude. Salience waveforms are plotted by electrode in panel A with reliable BSRs indicated. Panel B presents a bar graph of the average scalp score by group for each condition. Error bars represent bootstrapped confidence intervals.

LV1 ($p < .001$, 68.0% covariance explained) for verbal amplitude is presented in Figure 13 and represents an effect of task. Across groups, the control and maintenance condition are distinguished from the update condition (see panel B). The update condition is associated with negative BSR values and is associated with activity in a frontocentral ROI occurring around 300–400 ms and later in the time series for the frontal electrodes. The control and maintenance conditions are associated with positive BSR values and are associated with activity in temporal-parietal electrodes bilaterally, although the left side appears to show more reliable BSRs along the time series (see panel A).


A
IO1
IO2/VEOG
LO1
LO2
Fp1
Fpz
Fp2
AF7
AF3
AFz
AF4
AF8
F7
F5
F3
F1
Fz
F2
F4
F6
F8
FT7
FC5
FC3
FC1
FCz
FC2
FC4
FC6
FT8
T3/T7
C5
C3
C1
Cz
C2
C4
C6
T4/T8
TP7
CP5
CP3
CP1
CPz
CP2
CP4
CP6
TP8
TP9
TP10
P7/T5
P5
P3
P1
Pz
P2
P4
P6
P8/T6
P9
PO7
PO3
POz
PO4
PO8
P10
O1
Oz
O2
Iz
3.77
-200 ms
1000 ms
-4.88
BSR Threshold: ± 8 to ± 16

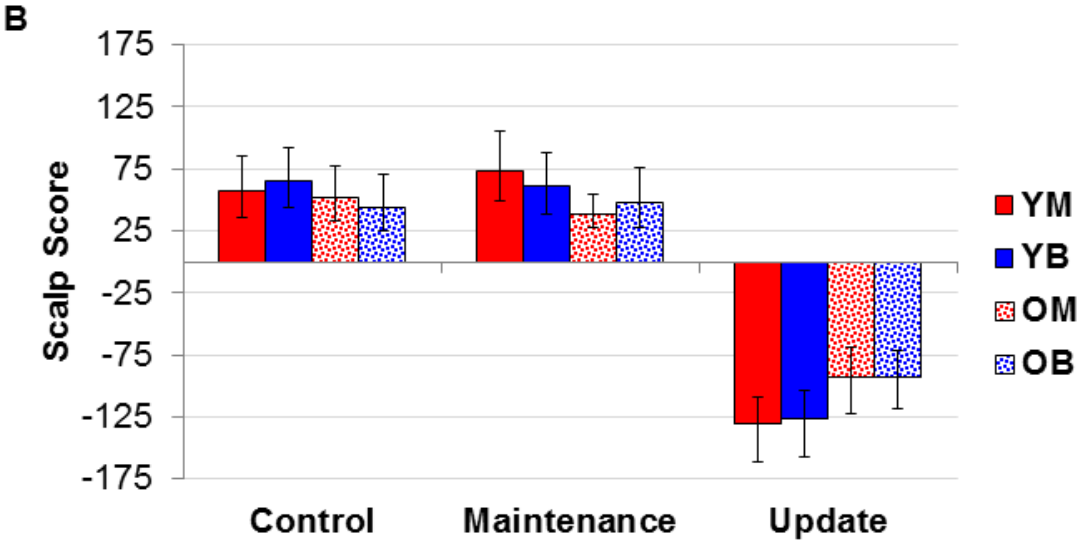
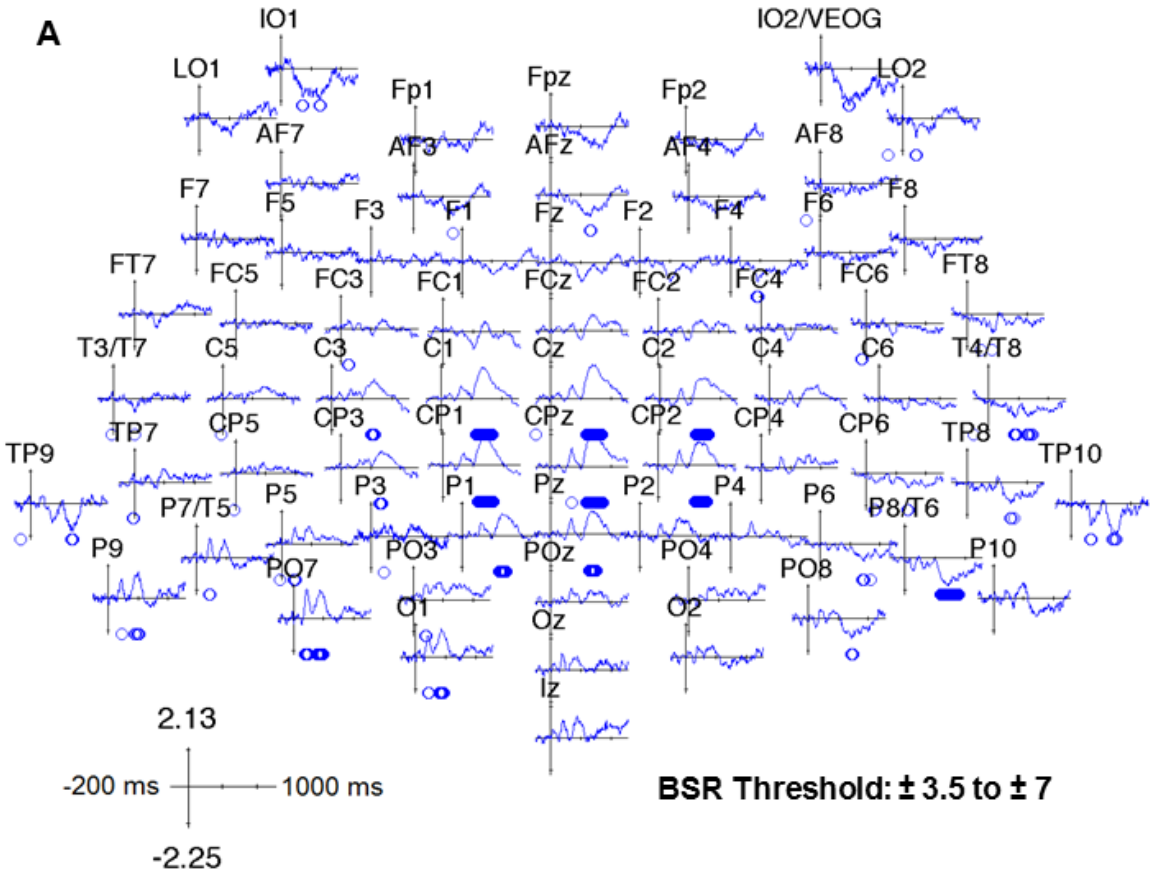

B
175
125
75
25
-25
-75
-125
-175
Scalp Score
Control
Maintenance
Update
YM
YB
OM
OB

Figure 13. PLS results for LV1 for verbal amplitude. Salience waveforms are plotted by electrode in panel A with reliable BSRs indicated. Panel B presents a bar graph of the average scalp score by group for each condition. Error bars represent bootstrapped confidence intervals.

LV2 (p = .002, 9.7% covariance explained) for verbal amplitude is presented in Figure 14 and represents an effect of age. Positive BSR values are associated with activity in centroparietal regions between 400–800 ms. Negative BSR values are associated with sparse frontal, temporal, and right-lateralized parietal-occipital areas of activation (see panel A). Younger adults display the positive BSR pattern during the control condition. Younger bilinguals display the negative BSR pattern during the update condition, although they show overlap with the younger monolinguals who do not differ from zero. Older adults display the negative BSR pattern for the control condition, but switch to the positive BSR pattern for the update condition that may represent a delayed latency shift in working memory processing (i.e., in the 400–800 ms time window). The groups do not reliably differ on the maintenance condition (see panel B).


A
IO1
IO2/VEOG
LO1
LO2
Fp1
Fpz
Fp2
AF7
AF3
AFz
AF4
AF8
F7
F5
F3
F1
Fz
F2
F4
F6
F8
FT7
FC5
FC3
FC1
FCz
FC2
FC4
FC6
FT8
T3/T7
C5
C3
C1
Cz
C2
C4
C6
T4/T8
TP7
CP5
CP3
CP1
CPz
CP2
CP4
CP6
TP8
TP9
TP10
P7/T5
P5
P3
P1
Pz
P2
P4
P6
P8/T6
P9
PO7
PO3
POz
PO4
PO8
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O1
Oz
O2
Iz
2.13
-200 ms
1000 ms
-2.25
BSR Threshold: ± 3.5 to ± 7

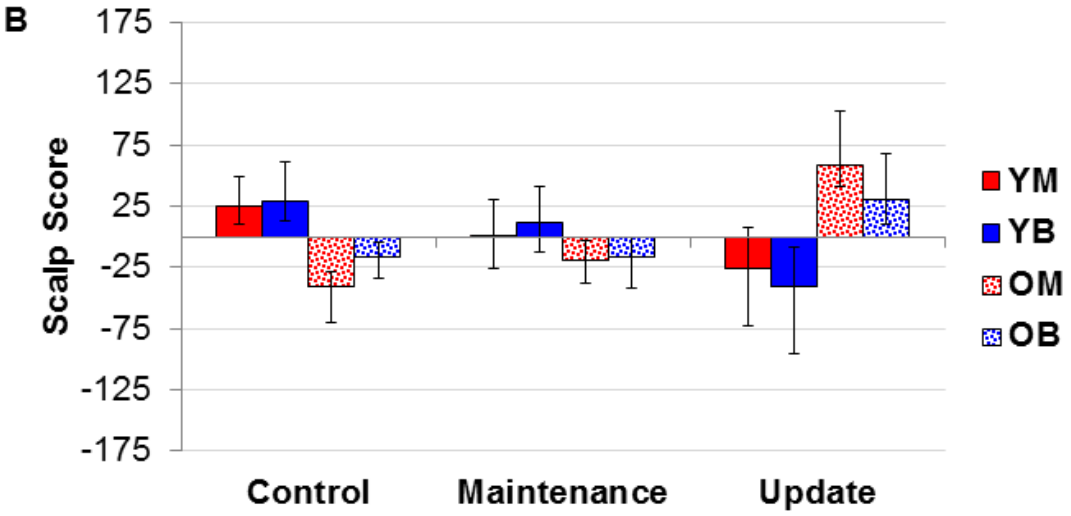
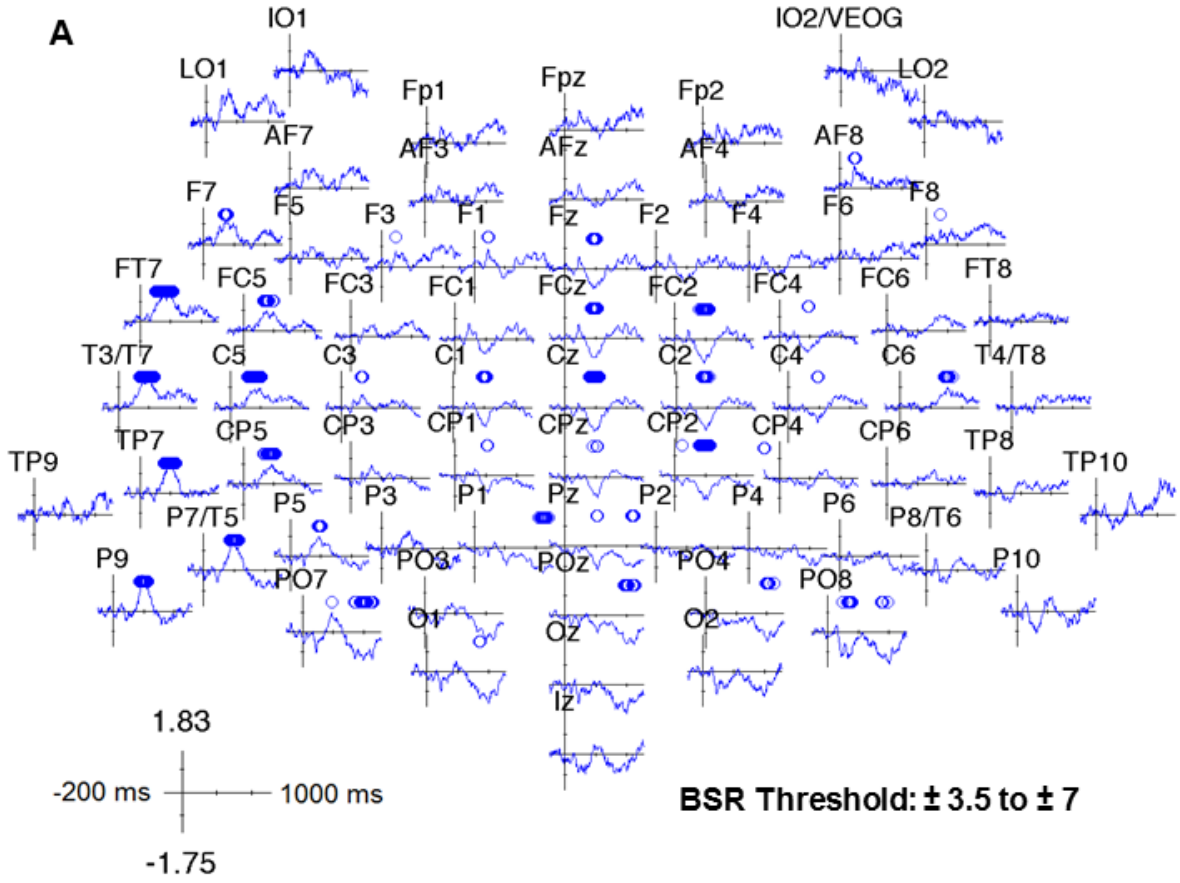

B
175
125
75
25
-25
-75
-125
-175
Scalp Score
Control
Maintenance
Update
YM
YB
OM
OB

Figure 14. PLS results for LV2 for verbal amplitude. Salience waveforms are plotted by electrode in panel A with reliable BSRs indicated. Panel B presents a bar graph of the average scalp score by group for each condition. Error bars represent bootstrapped confidence intervals.

LV3 (p = .015, 8.1% covariance explained) for verbal amplitude is presented in Figure 15 and represents an age by language interaction. In this third latent variable, positive BSR values are associated with a pattern of activity that is left-lateralized and negative values are associated with a more centralized pattern of activity (see panel A). Older monolinguals appear to use a different activation pattern across the maintenance and update conditions than the other three groups. Younger adults and older bilinguals use the negative BSR pattern for the maintenance condition whereas older monolinguals use the negative BSR pattern for the update condition. Younger adults and older monolinguals display the positive BSR pattern for the control condition but older bilinguals do not (see panel B).


A
IO1
IO2/VEOG
LO1
LO2
Fp1
Fpz
Fp2
AF7
AF3
AFz
AF4
AF8
F7
F5
F3
F1
Fz
F2
F4
F6
F8
FT7
FC5
FC3
FC1
FCz
FC2
FC4
FC6
FT8
T3/T7
C5
C3
C1
Cz
C2
C4
C6
T4/T8
TP7
CP5
CP3
CP1
CPz
CP2
CP4
CP6
TP8
TP9
TP10
P7/T5
P5
P3
P1
Pz
P2
P4
P6
P8/T6
P9
PO7
PO3
POz
PO4
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Oz
O2
Iz
1.83
-200 ms
1000 ms
-1.75
BSR Threshold: ± 3.5 to ± 7

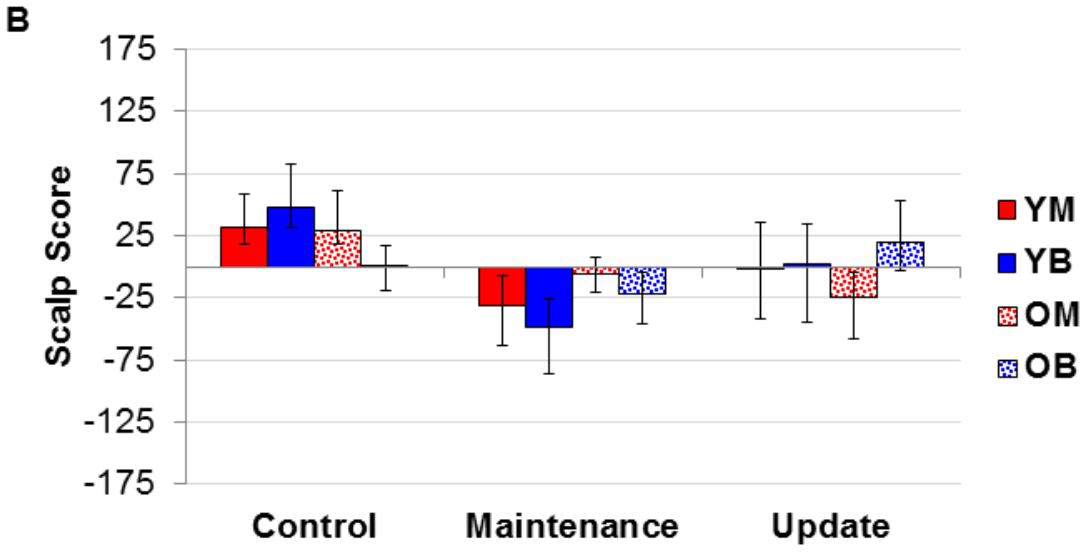
B
175
125
75
25
-25
-75
-125
-175
Scalp Score
Control
Maintenance
Update
YM
YB
OM
OB

Figure 15. PLS results for LV3 for verbal amplitude. Salience waveforms are plotted by electrode in panel A with reliable BSRs indicated. Panel B presents a bar graph of the average scalp score by group for each condition. Error bars represent bootstrapped confidence intervals.

MSE PLS Results for Probe Recognition

LV1 ($p < .001$, 39.8% covariance explained) for spatial MSE is presented in Figure 16 and represents an age by language interaction. BSR values are presented in the form of a heat map by electrode and by entropy timescale in panel A. Scalp maps plotted above the heat map show the BSR pattern across the head and are the average of five consecutive entropy timescales. The colour bar depicts the range of positive and negative BSR values presented in the heat map.

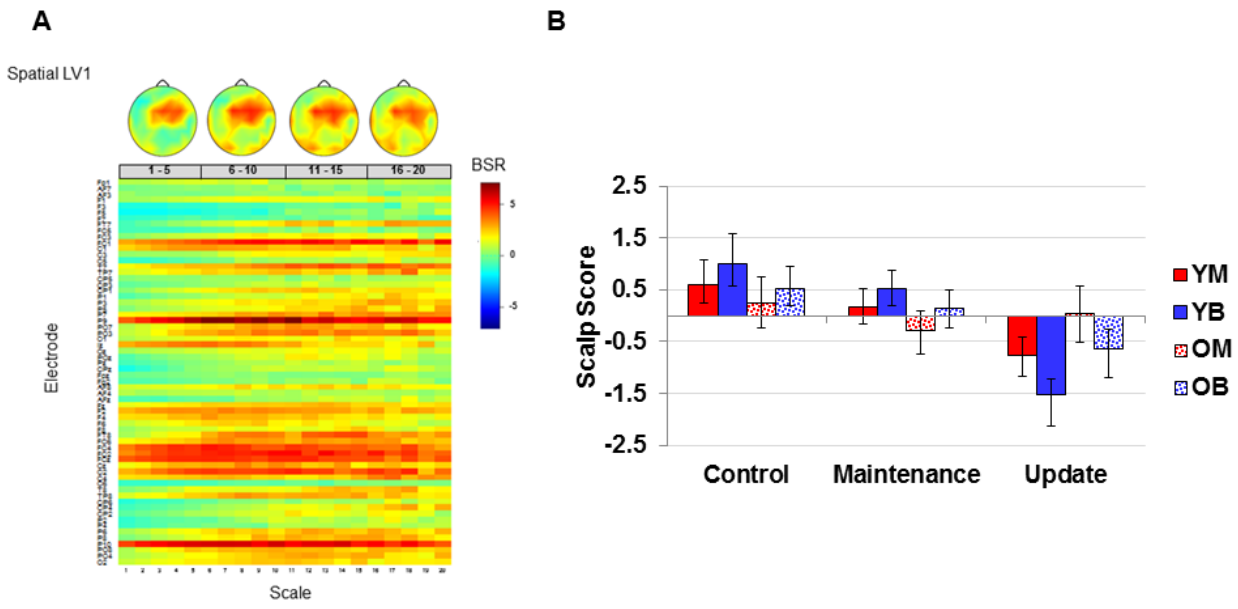

Figure 16. PLS results for LV1 for spatial MSE. A heat map of BSR values are plotted by electrode and entropy timescale in panel A. Panel B presents a bar graph of the average scalp score by group for each condition. Error bars represent bootstrapped confidence intervals.

For this first latent variable, positive BSR values are associated with a pattern of MSE that occurs bilaterally in frontocentral regions across all timescales and in posterior parietal regions at increasingly coarser timescales. Negative BSR values are associated with a pattern of MSE that occurs in left-frontal and midline centroparietal regions at finer timescales (see panel A). As shown in Figure 16, panel B, older bilinguals resemble the younger adults as all three groups switch from the positive BSR pattern to the negative BSR pattern as conditions become more effortful. Older monolinguals are unable to switch brain states across working memory conditions in the same way. This pattern is confirmed with linear trend analysis, with a significant group by condition effect, $F(3, 103) = 2.88$, $p < .05$, $\eta^2_p = .08$. This linear contrast was significant for the younger monolinguals ($p = .008$), younger bilinguals ($p < .001$), and the older bilinguals ($p < .05$), but not the older monolinguals ($p = .75$) (see panel B).

LV2 ($p < .001$, 22.3% covariance explained) for spatial MSE is presented in Figure 17 and represents an age by language interaction. Positive BSR values are associated with a pattern of MSE across all time scales that occurs bilaterally in centroparietal regions and is left-lateralized in frontal-temporal regions. Negative BSR values are associated with a pattern of MSE that is right-lateralized in frontal regions and some parietal activity (see panel A). Older monolinguals display the negative, more frontal BSR complexity pattern for the maintenance condition, whereas the older bilinguals and the younger adults do not. For the update condition, older monolinguals ramp up the positive, more centroparietal BSR complexity pattern, whereas the older bilinguals do not reliably differ from the younger adults. The groups do not reliably differ on the control condition.

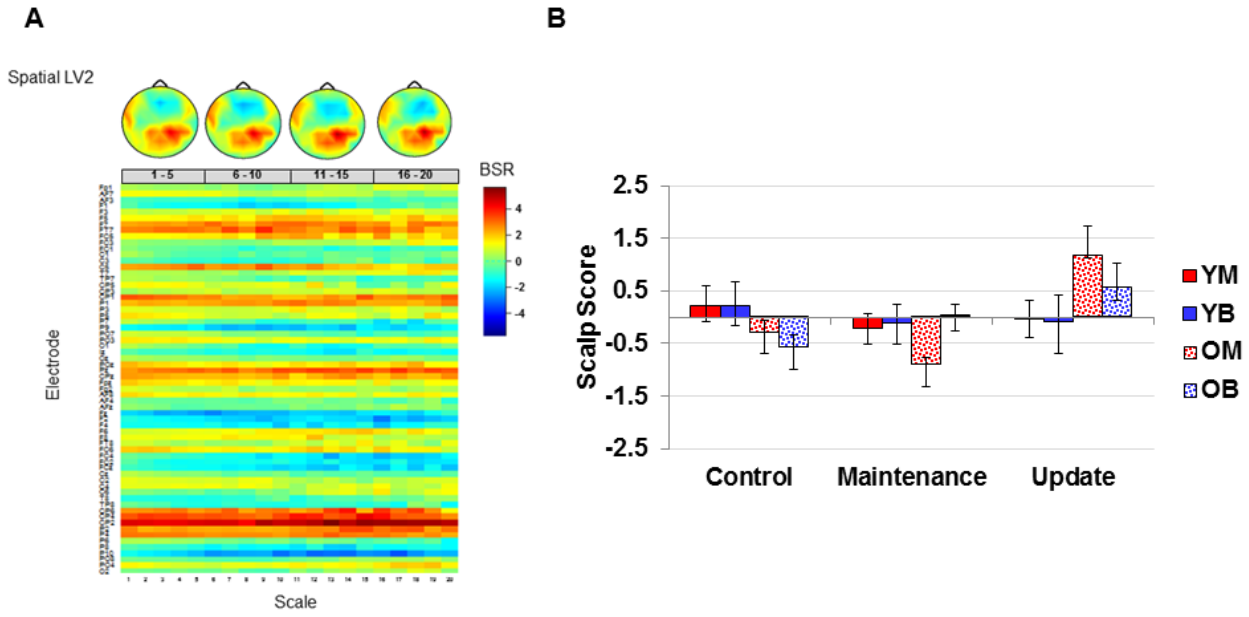

Figure 17. PLS results for LV2 for spatial MSE. A heat map of BSR values are plotted by electrode and entropy timescale in panel A. Panel B presents a bar graph of the average scalp score by group for each condition. Error bars represent bootstrapped confidence intervals.

LV3 ($p < .05$, 12.8% covariance explained) for spatial MSE is presented in Figure 18 and represents an age by language interaction. Positive BSR values are associated with a pattern of MSE that occurs strongly across all time scales in left-lateralized parietal-occipital regions, accompanied by some right frontal activity. Negative BSR values are associated with a pattern of MSE that occurs strongly in central electrodes across all time scales (see panel A). This latent variable pulls apart the younger bilinguals from the other three groups. The younger bilinguals display the negative, more centralized BSR pattern for the maintenance condition, whereas the other three groups do not. For the update condition, the bilinguals show the positive BSR pattern. This positive pattern may represent feedback between parietal-occipital and frontal regions, with

an eventual shift to more posterior regions that would be in line with recent models of bilingual neural processing (Grant, Dennis, & Li, 2014; Grundy, Anderson, & Bialystok, 2017a). Younger monolinguals show a negative BSR pattern for the update condition, but do not reliably differ from the older adults who overlap with zero. The groups do not reliably differ on the control condition (see panel B).

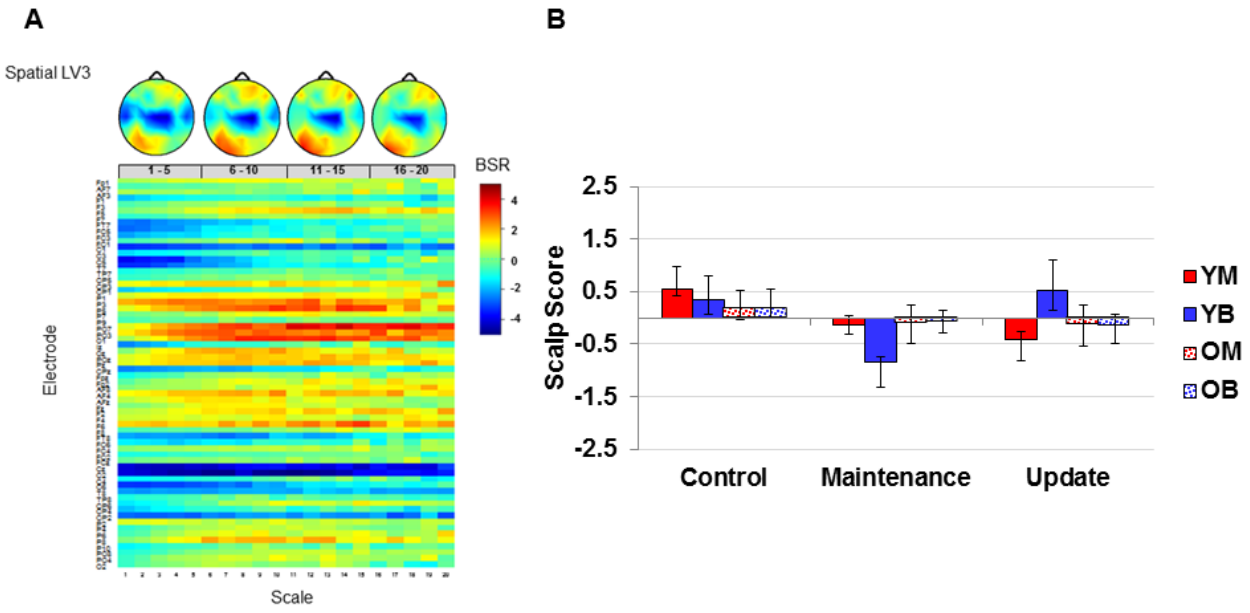

Figure 18. PLS results for LV3 for spatial MSE. A heat map of BSR values are plotted by electrode and entropy timescale in panel A. Panel B presents a bar graph of the average scalp score by group for each condition. Error bars represent bootstrapped confidence intervals.

LV1 ($p < .001$, 36.3% covariance explained) for verbal MSE is presented in Figure 19 and represents an effect of age. Positive BSR values are associated with a pattern of MSE that is left-lateralized in frontal and parietal regions, with the strongest parietal activity present at finer

time scales. Negative BSR values are associated with a pattern of MSE that is left-lateralized to fronto-temporal regions and right-lateralized centroparietal regions across all time scales (see panel A). Younger adults display an increase in scalp scores as conditions become more effortful, using the negative BSR pattern for the control condition and the positive BSR pattern for the update condition. Older adults do not display this relationship.

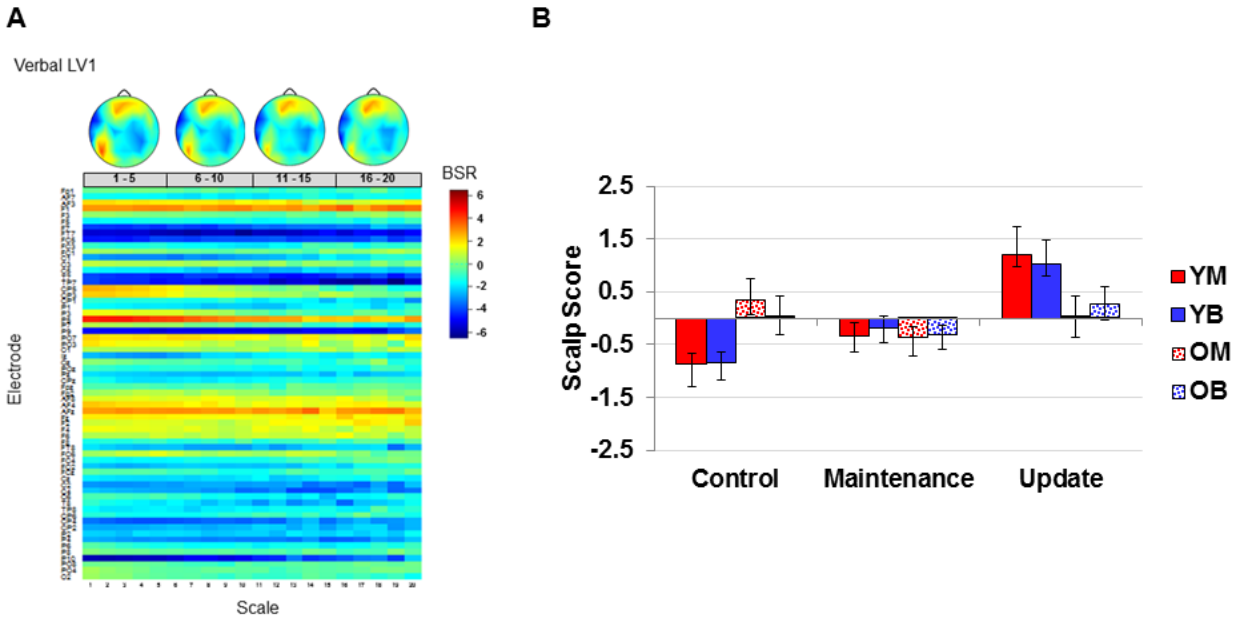

Figure 19. PLS results for LV1 for verbal MSE. A heat map of BSR values are plotted by electrode and entropy timescale in panel A. Panel B presents a bar graph of the average scalp score by group for each condition. Error bars represent bootstrapped confidence intervals.

LV2 ($p < .001$, 19.4% covariance explained) for verbal MSE is presented in Figure 20 and represents an effect of age. Positive BSR values are associated with a pattern of MSE that is left-lateralized in parietal-occipital regions and is accompanied by finer scale bilateral frontal activity that becomes more right-lateralized at coarser time scales. Negative BSR values are

associated with a pattern of MSE that occurs in some temporal and frontal regions (see panel A). Older adults display an increase in scalp scores as conditions become more effortful in that they use the negative BSR pattern for the control condition and the positive BSR pattern for the update condition. The majority of the younger adult effects are not reliable.

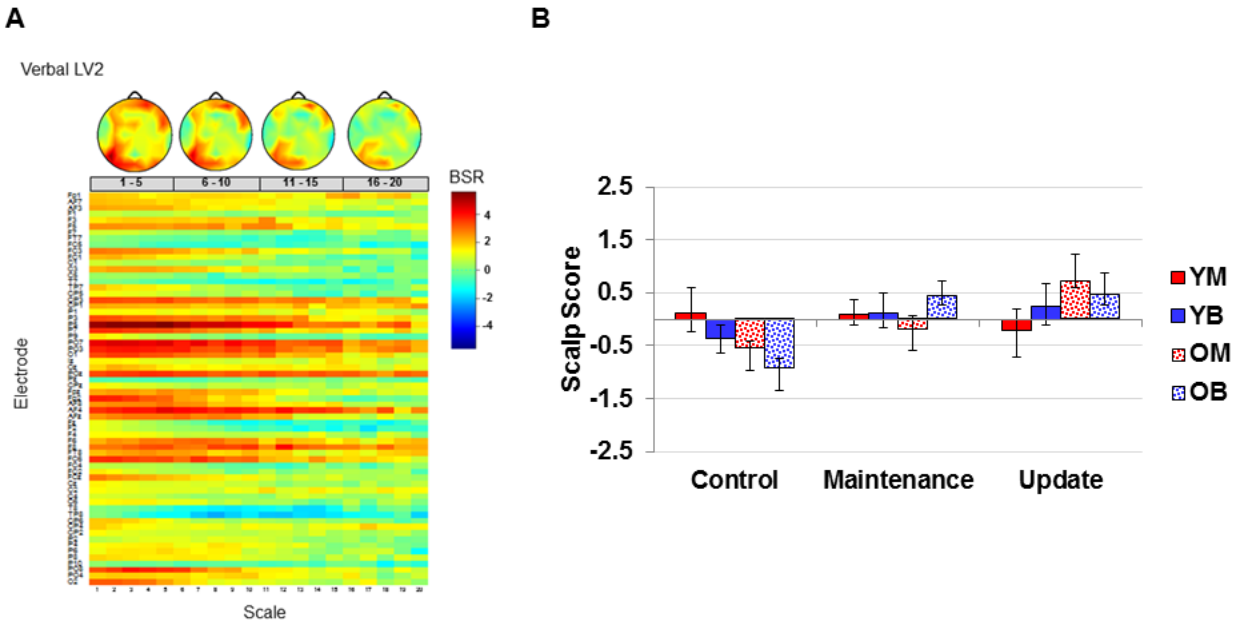

Figure 20. PLS results for LV2 for verbal MSE. A heat map of BSR values are plotted by electrode and entropy timescale in panel A. Panel B presents a bar graph of the average scalp score by group for each condition. Error bars represent bootstrapped confidence intervals.

LV3 ($p < .05$, 12.3% covariance explained) for verbal MSE is presented in Figure 21 and represents a language effect. Differences between monolinguals and bilinguals are present for both age groups and in somewhat equal measure. Positive BSR values are associated with a pattern of MSE that is largely centralized, however is left-lateralized in parietal-occipital regions and is right-lateralized in frontocentral regions for finer time scales. Negative BSR values are

associated with a pattern of MSE that is localized to far frontal and parietal regions (see panel A). The younger bilinguals in particular use a different pattern than the other three groups to shift between networks when performing the memory conditions. Younger bilinguals shift from the positive BSR pattern to the negative BSR pattern when moving from maintenance to update. Younger and older monolinguals both use the positive BSR pattern for the update condition. The older bilinguals do not reliably differ from zero across conditions. The older monolinguals display the negative BSR pattern for the maintenance condition, although they overlap with the older adult bilinguals. The groups do not reliably differ on the control condition.

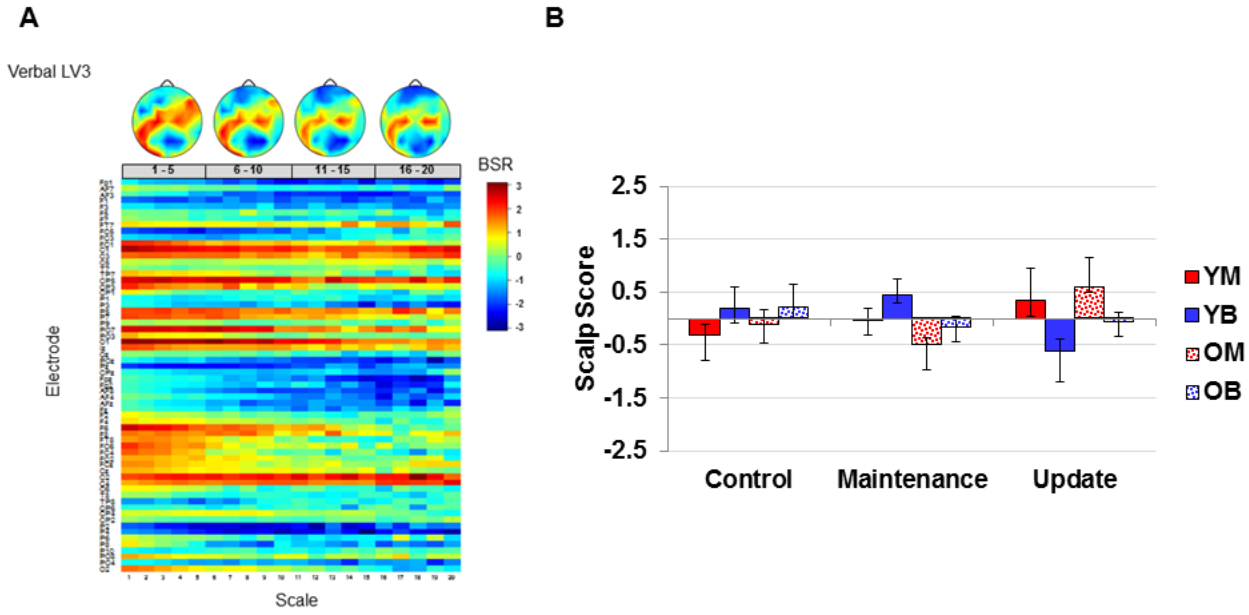

Figure 21. PLS results for LV3 for verbal MSE. A heat map of BSR values are plotted by electrode and entropy timescale in panel A. Panel B presents a bar graph of the average scalp score by group for each condition. Error bars represent bootstrapped confidence intervals.

A summary of the four PLS analysis results in terms of domain (i.e. spatial vs. verbal) and EEG measure (amplitude vs. MSE) is shown in Table 10.

Table 10.

Summary of PLS Results for Probe Recognition

Measure	Domain	LV	*p* value	% Covariance Explained	Min, Max BSR	BSR Figure Threshold	Effect Shown
Amplitude	Spatial	1	$p < .001$	69.8%	-12.8, 17.7	±9 to ±18	Task
		2	$p = .009$	8.6%	-5.4, 5.3	±2.5 to ±6	Age x Language
Amplitude	Verbal	1	$p < .001$	68.0%	-15.4, 8.8	±8 to ±16	Task
		2	$p = .002$	9.7%	-6.1, 6.5	±3.5 to ±7	Age
		3	$p = .015$	8.1%	-5.0, 6.8	±3.5 to ±7	Age x Language
MSE	Spatial	1	$p < .001$	39.8%	-1.7, 7.1	±7.1	Age x Language
		2	$p < .001$	22.3%	-3.3, 5.7	±5.7	Age x Language
		3	$p < .05$	12.8%	-5.0, 4.3	±5.0	Age x Language
MSE	Verbal	1	$p < .001$	36.3%	-6.5, 4.5	±6.5	Age
		2	$p < .001$	19.4%	-2.3, 5.6	±5.6	Age
		3	$p < .05$	12.3%	-3.1, 3.0	±3.1	Language

Brain-Behaviour Correlations

Correlations were run between individual scalp scores from each significant latent variable and the behavioural measures of accuracy and RT. *P*-values from the correlations were corrected using the Benjamini-Hochberg procedure to avoid Type I errors. For RT, none of the correlations survived correction, *p*s > .22. For accuracy, significant brain-behaviour correlations that survived correction, $p < .05$, are presented in Table 11 by group.

Table 11.

Significant Correlations Between Scalp Scores and Accuracy by Group

Language Group	Age Group	Domain	Condition	Measure	LV	Correlation	Adjusted *p*
Bilingual	Old	Spatial	Maintenance	MSE	LV1	-0.56	0.022
Bilingual	Old	Spatial	Update	MSE	LV1	-0.62	0.011
Bilingual	Old	Spatial	Maintenance	MSE	LV2	-0.53	0.033
Bilingual	Old	Verbal	Maintenance	MSE	LV1	0.75	< .0001
Bilingual	Old	Verbal	Update	MSE	LV1	0.65	0.004
Bilingual	Old	Verbal	Control	MSE	LV2	-0.52	0.033
Bilingual	Old	Verbal	Maintenance	MSE	LV2	-0.76	< .0001
Bilingual	Old	Verbal	Update	MSE	LV2	-0.58	0.011
Bilingual	Old	Verbal	Update	MSE	LV3	0.53	0.029
Bilingual	Young	Verbal	Control	Amplitude	LV1	0.60	0.012
Bilingual	Young	Verbal	Control	Amplitude	LV3	-0.63	0.011
Bilingual	Young	Verbal	Maintenance	MSE	LV2	-0.62	0.011
Monolingual	Old	Spatial	Maintenance	MSE	LV2	-0.63	0.011

The older bilingual group had multiple significant correlations between MSE scalp scores and accuracy. In the spatial domain, there were significant negative correlations between accuracy and maintenance scalp scores for LV1 and LV2, and between accuracy and the update scalp scores for LV1. However, the older bilingual scalp score group average for maintenance for LV1 and LV2 was not reliable as the 95% confidence intervals crossed zero (see Figures 16 and 17). Importantly though, the negative correlation between accuracy and update scalp scores for LV1 indicates that the more the older bilinguals loaded onto the negative scalp score pattern that was similar to the pattern shown in the younger adults, the higher older bilingual accuracy was (see Figure 16).

For LV1 of verbal MSE, the older bilinguals had positive correlations between maintenance and update scalp scores and accuracy. As shown in Figure 19, the older bilinguals on average had negative scalp scores for the maintenance condition, therefore this pattern does not benefit accuracy. For the update condition, older bilinguals do show the positive pattern, which is in the same direction as younger adults and would benefit accuracy, however the 95% confidence interval does cross zero and is therefore not reliable. For LV2 of verbal MSE, the older bilinguals have negative correlations with scalp scores and accuracy across all three conditions. As shown in Figure 20, the negative pattern for the control condition is beneficial for accuracy, however the positive patterns shown by the older bilinguals for the maintenance and update conditions are not beneficial for accuracy. Finally, for LV3 of verbal MSE, older bilinguals have a positive correlation with scalp scores and update accuracy, however the group average seen in Figure 21 is not reliable.

The younger bilinguals had a positive correlation between amplitude scalp scores and accuracy for the verbal control condition for LV1. As shown in Figure 13, the correlation

signifies that the positive pattern was beneficial to younger bilingual accuracy. For LV3 of verbal amplitude, the younger bilinguals displayed a negative correlation with accuracy for the control condition, however the group scalp score average is positive and therefore the pattern, which is in the same direction as the monolinguals, is not beneficial for accuracy (see Figure 15). For LV2 of verbal MSE, the younger bilinguals had a negative correlation with accuracy for the maintenance condition, however the group scalp score average was not reliable (see Figure 20).

Finally, the older monolinguals displayed a negative correlation between accuracy and scalp scores for LV2 for spatial MSE on the maintenance condition. This relationship indicates that the negative pattern shown by older monolinguals on maintenance in Figure 17 was beneficial for accuracy.

Discussion

Significant latent variables were found in all task conditions and for both types of EEG measure examined. These LVs identified distinct neural patterns corresponding to effects of task, age, and language group. For the spatial amplitude PLS analysis, the first significant latent variable indicated that the majority of the variance was due to task effects that was similar across groups (69.8% explained). The more effortful update condition was associated with frontocentral activity occurring at the P3 time window and later in the time series and parallels the stronger use of frontal resources for spatial recognition seen with the P3 ANOVA results in Chapter 3. The control condition was associated with left-lateralized activity in parietal-occipital electrodes that may represent perceptual processing. After accounting for the large amount of task-related variance, a significant age by language interaction emerged with the second latent variable. Here, the main finding was that older bilinguals resembled younger adults in terms of switching between networks and activation levels across working memory conditions. In contrast, older

monolinguals required more frontal resources during a later time window than their younger counterparts to perform the update condition, and greater activation in frontal regions during an earlier time window and in parietal-occipital regions during a later time window to maintain spatial information in working memory.

Correspondingly, the first significant latent variable for verbal recognition represented a strong task effect (68.0 % explained) across groups. Again, the update condition required frontocentral activity during the P3 time window and later in the time series. The less effortful control and maintenance conditions utilized bilateral temporal-parietal activity that tended to be more left-lateralized. After accounting for task effects there was a second significant latent variable that represented an effect of age. Notably, for the update condition, older adults but not younger adults drew upon later occurring centroparietal activity from 400–800 ms that may represent a delayed latency shift in working memory processing with aging. This aligns with the behavioural results from Chapter 3 showing overall slower RT with aging, particularly for the update condition. The third significant latent variable for verbal recognition represented an age by language interaction. For this result, younger adults and older bilinguals, but not older monolinguals, used a similar centralized pattern of neural activity to maintain verbal information in working memory. Older monolinguals drew upon this centralized pattern of activity for the update condition, whereas younger adults and older bilinguals did not. For the control condition, the younger adults and older monolinguals, but not the older bilinguals, activated a long-range left-lateralized pattern of activity. Therefore, as with the age by language interaction seen in spatial recognition, for verbal recognition there was evidence that older bilinguals switched across network patterns in a similar manner as younger adults for the two memory conditions (i.e., maintenance and update).

The amplitude PLS results indicated that for both spatial and verbal recognition, task effects encompassed the majority of the variance, and may explain why it was difficult to separate out language group differences in Chapter 3. The updating condition required frontocentral activity irrespective of domain, suggesting that this activity is related to attentional control common to both tasks, whereas the other conditions (i.e., spatial control, and verbal control and maintenance) showed largely left-lateralized activity in temporal-parietal-occipital regions that may relate to perceptual judgement (posterior intraparietal sulcus, Yang, Szeverenyi, & Ts'o, 2008) or the use of language to aid perceptual judgment (left posterior superior temporal gyrus and left inferior parietal lobule, Tan et al., 2008).

Of interest was the finding that after parsing out the task-related variance, the second latent variable for the spatial task indicated that older adult bilinguals displayed a similar pattern of activation as younger adults across conditions, whereas older monolinguals required additional frontal resources for the spatial update condition and additional activation of frontal and parietal-occipital regions for the spatial maintenance condition. Reliance on frontal areas to perform the spatial task may be necessary due to the demands of this task, as older adults had greater difficulty with the accuracy rates shown for spatial update condition. This result supports the prediction that older monolinguals would rely more on frontal activation than older bilinguals during spatial working memory. For the third latent variable of the verbal task, older bilinguals resembled younger adults for the verbal maintenance and update conditions, whereas older monolinguals displayed the centralized pattern that was shown for the other groups for the maintenance condition during the update condition. This result of older bilinguals engaging in a similar neural pattern as younger adults aligns with the cognitive control functional activation work by Gold et al. (2013).

The results from the MSE PLS analyses did not show large task effects as was seen with amplitude, but instead uncovered multiple group effects and interactions. The first significant latent variable from the spatial MSE PLS again demonstrated that older bilinguals switched across brain states in the same linear manner as younger adults to perform the different task conditions. This involved a shift from a combination of frontocentral regions and coarse/distributed posterior parietal to fine/localized left-frontal and midline to right-lateralized centroparietal MSE to perform the more effortful update condition. The brain-behaviour correlations in the spatial domain indicated that the pattern shown for the update condition by the younger adults and the older adult bilinguals was beneficial for older bilingual accuracy. The older monolinguals were unable to use this processing strategy, but instead used a neural pattern that was more representative of the second latent variable. For the second significant latent variable, across time scales older monolinguals used a slightly right-lateralized frontal region with some lateral temporal-parietal processing for the maintenance condition and an elevated pattern of MSE across time scales bilaterally in centroparietal regions and largely left-lateralized in frontal-temporal regions for the update condition. The pattern shown by older monolinguals on the maintenance condition was associated with higher accuracy and supports the interpretation that the second LV is more representative of older monolingual processing. The third significant latent variable isolated a distinct neural pattern for the younger bilingual group. Younger bilinguals relied on strong central complexity across all time scales for the maintenance condition. Younger monolinguals also loaded onto this centralized pattern for the update condition, but younger bilinguals recruited left-lateralized parietal-occipital regions, accompanied by some right frontal complexity that may represent a long range communication

mechanism that could underlie an eventual adaptation to more posterior processing (Grant, Dennis, & Li, 2014; Grundy, Anderson, & Bialystok, 2017a).

Verbal MSE drew out stronger effects of aging than did spatial MSE. The first significant latent variable represented a network shift in younger adults, where a strongly left-lateralized fronto-temporal and right-lateralized centroparietal network across all time scales was used for the control condition, and a shift to left-lateralized anterior frontal accompanied by parietal complexity, with the strongest parietal complexity present at fine time scales, was used for the update condition. Older adults were instead represented by the results of the second significant latent variable. Here, older adults used select temporal and frontal regions, particularly at coarse time scales for the control condition and then switched to a wide range pattern of MSE that was left-lateralized in parietal-occipital regions, and was accompanied by fine scale bilateral frontal complexity that became more right-lateralized at coarse time scales for the update condition. The brain-behaviour correlations in the verbal domain indicated that the patterns shown by the older adult bilinguals for the maintenance condition of LV1 and the maintenance and update conditions of LV2 were not beneficial for accuracy. After accounting for these age effects, the third significant latent variable represented an overall language group effect, although the effects were more reliable in younger bilinguals than older bilinguals. The younger bilinguals used a reliable pattern for the maintenance condition that was largely centralized, but showed strong left-lateralization in parietal-occipital regions and right-lateralization in frontocentral regions at fine time scales. Monolinguals in both age groups displayed this centralized pattern for the update condition, but younger bilinguals showed a strong pattern of MSE that was localized to anterior frontal and parietal regions for the update condition. The pattern displayed for younger

bilinguals during the verbal update condition again provides support for the use of a frontoparietal long range communication system.

The use of MSE provided additional information into how age and language group processing differences manifested across working memory conditions. The relationship between amplitude and signal entropy is based on the inherent variability of the waveform. When a waveform is highly predictable, for example as with a sine wave, entropy will be low. In contrast, when a waveform is highly variable in frequency and amplitude entropy will be high (Heisz & McIntosh, 2013). Thus, MSE values indicate how adaptable the ERP waveform is. As discussed, time-locking this calculation to the stimulus and assessing the variability across multiple time scales ensures that the entropy value is not due to noise. If neural processing is modified in response to condition demands through frequency and amplitude changes in the waveform, then corresponding changes in the patterns of MSE are expected. The spatial MSE results aligned with the spatial amplitude findings that older bilinguals resembled younger adults in terms of switching brain states across conditions that mapped onto localized time scale complexity in a left-frontal and midline to right-centroparietal MSE network to perform the more effortful update condition. Older monolinguals, in contrast, required a broad region of centroparietal complexity along with left-lateralized but some right hemisphere complexity in frontal-temporal regions that occurred across fine and coarse time scales. In the Heisz et al. (2015) MSE study, older adults who engaged in physical activity and displayed more local than distributed processing showed better working memory performance. The broad network of MSE shown in older monolinguals may underlie the elevated activation pattern that was shown with the spatial amplitude PLS results. Younger bilinguals displayed an additional network pattern in which spatial updating was largely localized to left-lateralized posterior regions, accompanied by

some right frontal complexity. The younger bilingual MSE pattern from the third latent variable may correspond to prior MSE work that showed younger bilinguals tend to rely more on increased signal variability localized to the posterior regions for management of attention with perceptual conflict (Grundy, Anderson, & Bialystok, 2017b).

The MSE results for the verbal task revealed a different pattern than the spatial task. The first two latent variables distinguished separate neural network patterns for younger and older adults. For the verbal update condition, younger adults utilized a focal set of left-lateralized anterior frontal and parietal regions, whereas older adults made use of a left-lateralized posterior region with bilateral frontal activation at fine time scales (i.e., local processing). These patterns of results are consistent with the HAROLD (Cabeza, 2002) model of functional brain reorganization in aging in which younger adults displayed left-lateralization for the verbal task and older adults required bilateral, frontal complexity. Finally, the third pattern indicated that younger bilinguals in particular had a network of MSE that occurred in anterior frontal and parietal regions for the update condition, although this broad range functional connection appeared to be more central on the scalp as opposed to the positive scalp score pattern seen with the third latent variable of the spatial task that was left-lateralized posteriorly and right-lateralized anteriorly. The relevance of these network patterns for bilingual memory processing and cognitive reserve in aging are explored further in the general discussion.

Chapter 5. General Discussion

The effects of bilingualism and aging on working memory were examined using three approaches. Each study built upon the previous to incorporate more sensitive measures that will help understand working memory across the lifespan. The overarching hypothesis was that bilinguals will show better performance than monolinguals on working memory tasks that require high levels of attentional control and involve nonverbal stimuli. In contrast, poorer performance by bilinguals than monolinguals was expected when the task involved verbal stimuli. The reasoning behind this latter hypothesis is that bilingual verbal processing should be negatively impacted by difficulties with lexical retrieval. These predictions were illustrated in the Attentional Control and Retrieval Access (ACRA) model presented in Chapter 1 (see Figure 2). In this model, aging should have an overall negative impact on memory performance, whereas high vocabulary knowledge/experience should have a compensatory effect for verbal tasks. These predictions were examined in two studies with different participants using three analytic approaches. In both studies, groups were matched on background measures apart from English vocabulary knowledge, and a consistent pattern of higher vocabulary scores in monolinguals than bilinguals and older adults than younger adults was shown. Chapter 2 presented behavioural data from younger and older adult bilinguals and monolinguals across a variety of tasks that involved working memory. Chapter 3 examined the neural correlates of attentional control in working memory by analyzing mean amplitude of the P3 ERP component. Finally, Chapter 4 used the multivariate approach of PLS to examine neural network amplitude and signal variability patterns across working memory conditions using the EEG recognition data from Chapter 3. The ACRA model predictions will now be discussed in terms of the findings.

At the behavioural level, the findings reported in Chapter 2 indicated that group differences in working memory performance were dependent on the type of task administered. In the verbal domain, the star counting working memory task required participants to count stars out loud, while concurrently managing switching cues (i.e., forward or backward counting direction) and rule (counting by 1s or 2s) demands. In line with the verbal and retrieval access factors in the ACRA model, bilinguals were slower than monolinguals to count stars but showed equivalent performance once vocabulary knowledge was controlled. However, controlling for vocabulary did not counteract slower performance due to aging, and age-related differences in processing speed were most apparent for the conditions with the lowest attentional demands and the highest. There were no age or language group differences in star counting accuracy.

In the nonverbal domain, a modified flanker task with working memory demands manipulated by arrow response direction and a nonverbal recent probe working memory interference task were performed. The nonverbal stimuli for the recent probe task were visual symbols. For the flanker task, age-related slowing for RT was especially prominent for the most effortful conditions. Monolinguals showed an unexpected effect of faster RT than bilinguals during conflict blocks. Older adults also showed a larger RT cost than younger adults of having to remember to respond in the opposite direction, but language groups were equivalent in terms of this working memory cost score. For the nonverbal recent probe working memory task, aging negatively impacted both accuracy and RT. In addition, bilinguals were faster than monolinguals on proactive interference trials and had a smaller interference cost (replicating the nonverbal task results in Bialystok et al., 2014). Therefore, results of the recent probe task results fit with the ACRA model in terms of the nonverbal and high demand on attentional control in working memory factors.

In Chapter 3, behavioural results from the running memory procedure were presented. For the spatial task, age-related declines in accuracy and RT were shown and were especially pronounced for the difficult spatial update condition that required the most attentional control. The verbal task produced similar findings, with lower accuracy and slower RT for older than younger adults. Age effects on verbal RT were more pronounced for the control and update conditions than for the maintenance condition. There were no language differences in RT for verbal recognition, but monolinguals were faster than bilinguals on the verbal star counting task in Chapter 2, which involved production. Better performance by monolinguals than bilinguals on a verbal memory task that involves production is consistent with the findings from the Fernandes et al. (2007) study. Therefore, production is another factor that can be added to the ACRA model that has adverse effects on bilingual and older adult performance, but not younger adult monolingual performance.

In both studies, numbers were classified as verbal stimuli. As mentioned in Chapter 2, Oberauer, Süss, Schulze, Wilhelm, and Wittman (2000) provided evidence based on factor analysis and structural equation modeling with behavioural data that verbal memory and numerical working memory are part of the same construct, whereas spatial working memory is separate. Prior work has found poorer performance by bilinguals than monolinguals on digit span tasks (Mägiste, 1980; Ratiu & Azuma, 2015) or no language group differences on digit span tasks but poorer word recall (Fernandes et al., 2007). Chincotta and Underwood (1997) showed that for tests of number span with Spanish-English bilinguals, recall was influenced by both the language the number was written in and whether the number was presented in words or as digits. Better number span performance was shown for the dominant language (Spanish) and for digit presentation over word presentation. In addition, an articulatory suppression manipulation

influenced between-language effects for word presentation but not digit, suggesting that language processing effects in working memory performance are stronger for words than digits. Therefore, in terms of the verbal-nonverbal dimension in the ACRA model, a stimulus gradient of words, then digits, then shapes, and finally, spatial representations is proposed.

Work with visual recognition of letters and numbers in younger adult native English speakers has shown that letter recognition activated the left mid-fusiform and inferior temporal gyri more than numbers, whereas number recognition activated the right lateral occipital area more than letters, indicating inherent neural representational differences during the visual recognition of these two types of stimuli (Park, Hebrank, Polk, & Park, 2012). The left intraparietal sulcus is activated when making ordinal decisions about letters or numbers (i.e., are stimuli in alpha or numeric order) and this brain region is also involved in remembering the presentation order of letter stimuli (Attout, Fias, Salmon, & Majerus, 2014). There is also evidence from research in mathematical cognition with bilinguals that numerical problem solving using exact as opposed to approximate quantities relies on brain areas involved in language processing (Venkatraman, Siong, Chee, & Ansari, 2006). For the current studies, the choice of digits as stimuli was made from a practical standpoint to maintain consistency with the method of presentation in the literature where they were classified as verbal tasks. Although digits are not as verbal in nature as words, they share more commonalities with words than with visuospatial representations in memory.

The neural correlates of maintenance and updating in working memory were examined in Chapter 3 in relation to mean P3 amplitude, an ERP component that is associated with working memory processing (Amin, Malik, Kamel, Chooi, & Hussain, 2015; Donchin, 1981). The neural data must be interpreted with respect to the behavioural findings from the running memory

procedure showing that for mean accuracy and RT, there were age-related declines in performance but no effects of language group. The absence of language group differences during the study phase suggests that bilinguals and monolinguals engaged in similar processing of spatial and verbal stimuli at this stage, whereas age differences varied by domain. Older adults required larger P3 amplitude than younger adults to study verbal items and the effect of age was marginal for spatial items. The neural pattern in younger adults appeared to be more efficient than in older adults when studying verbal items, as the younger adult P3 increased to the level seen in older adults only for the more effortful update condition. Younger adults may be better able to conserve attentional resources than older adults, showing larger P3 amplitude only for the most difficult conditions. The diminished effects in the spatial task may have been due to the difficulty of the task or task processing may have involved other brain regions not taken into account by the selected ROIs. These results suggest that older adults require greater cognitive effort as indexed by P3 amplitude to study stimuli in working memory. This level of overactivation in older adults than in younger adults to perform tasks supports the CRUNCH model of aging (Reuter-Lorenz, & Cappell, 2008). Alternatively, older adults may have had a harder time disengaging from irrelevant stimuli in the control and maintenance conditions and therefore show larger P3 amplitude to these items relative to younger adults.

During spatial recognition, there were no language group differences in P3 activation. Both age groups used similar levels of frontal resources to perform the task, but younger adults had significantly higher centroparietal P3 amplitude than older adults. In addition, younger adults had higher amplitude than older adults for the two memory conditions. For verbal recognition, older adults required more frontal resources than younger adults for the control and maintenance condition, but the age groups had similar levels of frontal activation for the update condition.

Younger adults had higher amplitude than older adults at the centroparietal ROI as was shown with the spatial task. A language group interaction was present for verbal recognition. Monolinguals displayed a graded increase in P3 amplitude across conditions at both ROIs, whereas bilinguals showed a pattern of similar amplitude for control and maintenance and then increased amplitude for the update condition. The bilingual neural pattern at recognition parallels what was shown in younger adults during the study phase, and is arguably a better allocation of attentional resources as P3 amplitude increases only for effortful conditions. The greater frontal activation that was seen with aging, mainly in the verbal task, supports the PASA model (Davis, Dennis, Daselaar, Fleck, & Cabeza, 2008). Younger adults had stronger centroparietal activation across tasks than older adults, leading to better working memory performance. The language group differences for P3 amplitude were limited, and did not support the predictions from Chapter 3 that were based on the larger P3 amplitude for bilinguals than monolinguals seen in the cognitive control task literature.

The PLS results from Chapter 4 expanded the range of the neural data by examining the patterns seen across conditions to the whole brain. It is important to note that the spatial resolution of the effects found in Chapters 3 and 4 must be interpreted cautiously, as there is currently no method to localize the number of internal generators for a given ERP signal with high precision (Luck, 2005). The results from the current studies give a general estimation of group differences in working memory processing patterns that are based on summations at the level of the scalp. These findings will have to be further verified with the higher spatial resolution of fMRI. The spatial amplitude PLS revealed an important age by language interaction once the large effects due to task were accounted for. Older bilinguals resembled the pattern of activation seen in younger adults whereas older monolinguals required additional frontal

resources for the spatial update condition and additional activation of frontal along with parietal-occipital regions for the spatial maintenance condition. For verbal amplitude, once task effects were accounted for there was a significant effect of age and a significant age by language group interaction. The age effect revealed that older adults but not younger adults, loaded onto a pattern showing a delayed latency shift in centroparietal regions for verbal updating. For the second interaction, older bilinguals resembled younger adults for the verbal maintenance and update conditions, whereas older monolinguals displayed the centralized pattern that was shown for the other groups for the maintenance condition during the more effortful update condition. In summary, older bilinguals resembled the younger adult pattern for the spatial task and for the verbal task once a delayed age-related processing effect was accounted for. The finding in which older bilinguals required fewer frontal resources than older monolinguals for the spatial task is in line with the study predictions and incorporated into the ACRA model.

Effects similar to those found for amplitude were shown for the first significant latent variable from the spatial MSE PLS. Analyses of signal variability showed that older bilinguals resembled younger adults, displaying a pattern of localized processing in a left-frontal and midline to right-centroparietal MSE network to perform the update condition. The correlations with behaviour indicated that for the update condition, the older bilinguals who loaded onto the same pattern as the younger adults were more accurate. Older monolinguals displayed a separate pattern of signal variability for the update condition from the second latent variable in which they required a broad region of centroparietal complexity along with left-lateralized but some right hemisphere complexity in frontal-temporal regions that occurred across fine and coarse time scales. This MSE pattern in older monolinguals may be related to the pattern of overactivation that was seen with spatial amplitude that was not present in older bilinguals.

Younger bilinguals engaged a separate spatial MSE network pattern in which updating was largely localized to left-lateralized posterior regions accompanied by some right frontal complexity across time scales, representing a long-range pattern of processing that is dominant in posterior regions.

The verbal MSE results separated neural patterns that characterized younger adults with the first latent variable and older adults with the second latent variable. For the update condition, younger adults used select left-lateralized anterior frontal and parietal regions at fine time scales, whereas older adults made use of left-lateralized posterior region with bilateral frontal activation also at fine time scales. For the third latent variable, younger bilinguals used a centralized anterior frontal and posterior parietal region for the verbal update condition. The spatial MSE findings align with the spatial amplitude findings of older bilinguals having a more youthful neural signature across conditions, whereas although there was evidence of this pattern with verbal amplitude it was not shown with verbal MSE and in fact, the majority of verbal MSE patterns were not beneficial for older bilingual accuracy. Younger bilinguals appear to use more anterior-posterior patterns of complexity to support working memory performance, with more posterior regions used for the spatial task.

Across two brain measures, amplitude and MSE, older adult bilinguals displayed similar activation and brain state patterns as younger adults, although more so in the spatial domain. In addition, the evidence from the brain-behaviour correlations indicated that it was the youthful spatial MSE update pattern that was adaptive for older adult bilingual accuracy. In contrast, older adult monolinguals were unable to utilize the same pattern of brain network dynamics during working memory recognition. As these results were found in healthy older adults, these data contribute to uncovering the neural mechanisms associated with cognitive reserve in aging for

older adult bilinguals (i.e., a more youthful neural signature). Hernández, Costa, and Humphreys (2012) suggested that the bilingual selective attention system is enhanced in a top-down manner rather than bottom-up, as bilinguals are less affected than monolinguals by irrelevant items in working memory during visual search. This reasoning also helps explain why bilinguals outperform monolinguals on the recent probe task where interference from a no-longer relevant stimulus must be overridden at the memory recognition stage. Thus, the neural network patterns uncovered by PLS analysis that were associated with bilingualism, in particular for updating the contents of working memory and refocusing attention away from no longer relevant stimuli, may underlie a top-down attentional control system that aids working memory processing. A proposed neural model of attentional control in working memory for bilinguals would therefore involve two major components. First, older adult bilinguals displayed the same network patterns as younger adults to adapt to more effortful task demands, suggesting that older bilinguals use a more flexible attentional control system mainly for nonverbal tasks. Second, younger bilinguals are able to utilize a pattern of frontal-parietal MSE for updating that is more posterior for spatial working memory, and supports prior work with younger adult bilinguals, attention, and MSE (Grundy, Anderson, & Bialystok, 2017b).

To conclude, the studies in the current dissertation investigated working memory processing with aging and bilingualism in terms of attentional control processing and stimulus domain. Both factors were influential and produced a complex set of behavioural and neural results. Bilinguals outperformed monolinguals when the task involved nonverbal interference resolution. Monolinguals surpassed bilinguals when the task involved verbal production. After accounting for task and age-related variance, older adult bilinguals were shown to have a more youthful neural signature in terms of the patterns displayed across working memory conditions

that was associated with accuracy benefits in the spatial domain. Older adult monolinguals did not use these patterns and required additional frontal resources for the difficult spatial update condition. Finally, younger bilinguals were shown to utilize long-range, frontal-parietal MSE patterns for the more effortful updating conditions that may correspond to adaptations to a top-down attentional control mechanism. In Figure 1, selective attention was depicted as the underlying mechanism behind language control, executive control, and working memory. Based on the evidence across all three studies this conceptualization may be too absolutist and therefore problematic in describing how bilingualism may impact working memory processing. In contrast, the ACRA model relates working memory differences between language groups to varying levels of attentional control and domain, and thus allows for stronger predictions to be made of when the groups may diverge on either behavioural and/or neural measures. To conclude, the effects of bilingualism are complex and subtle, and as was shown by this series of studies, a single study using simple behavioural measures or neural measures that are too restrictive in nature can fail to capture them. It is the hope that the results from the current dissertation will promote further research into the validity of ACRA model of bilingual working memory using both behavioural and neuroscience measures.

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Appendix A

A Sample Card in the Working Memory Condition of the Star Counting Task

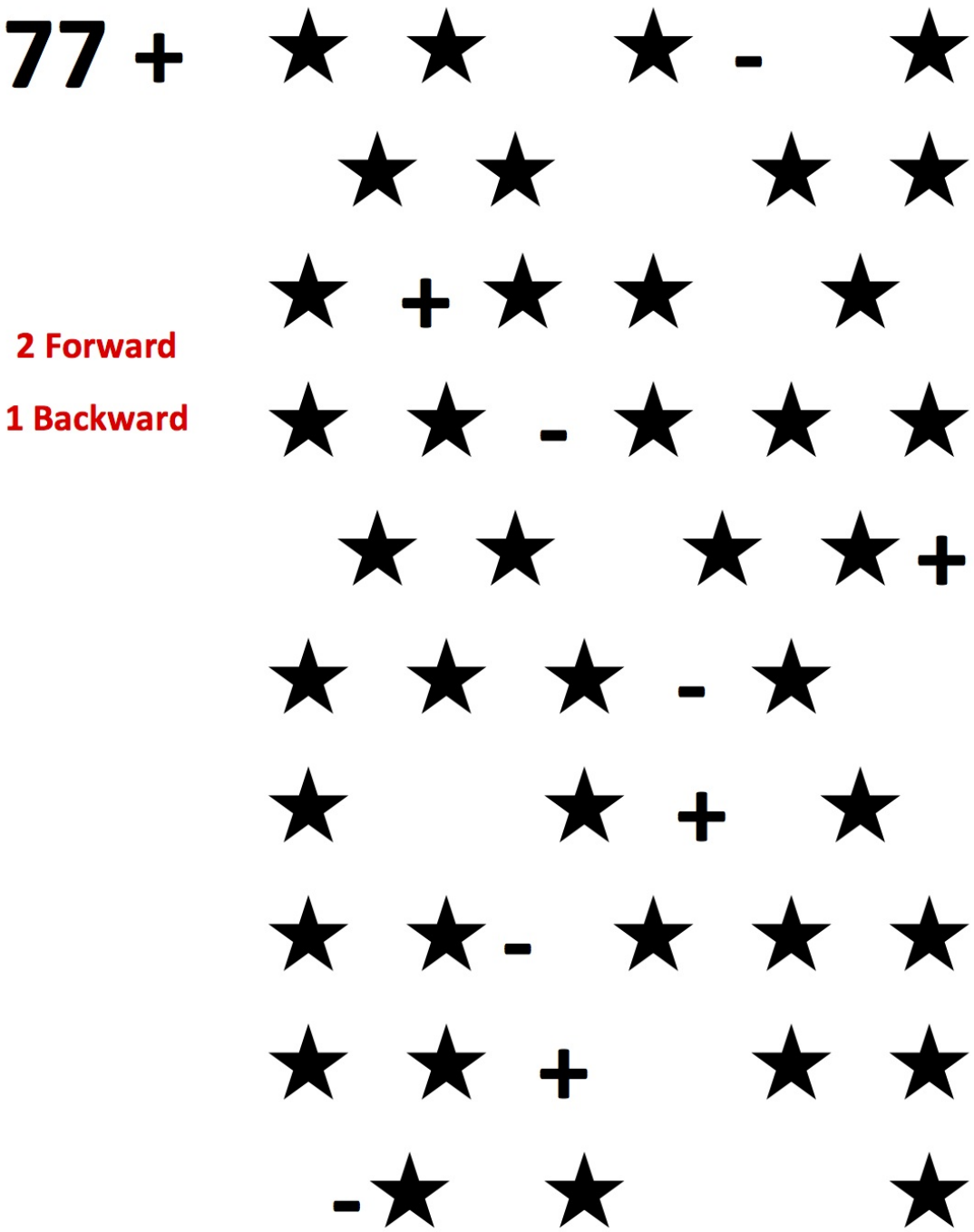
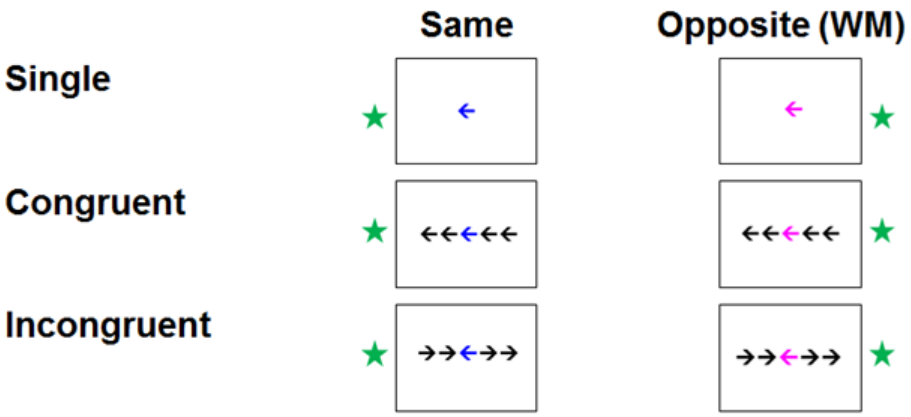
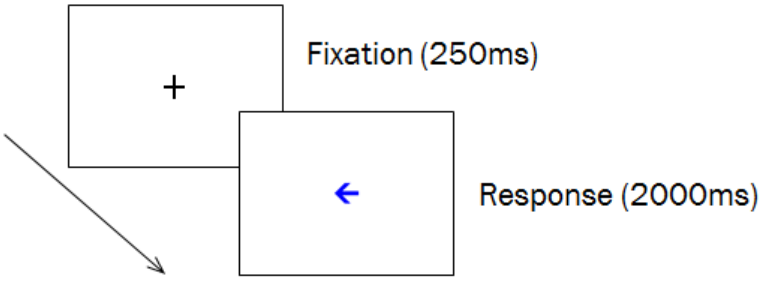


Image adapted from Das-Smaal, de Jong, & Koopmans, 1993.

Appendix B

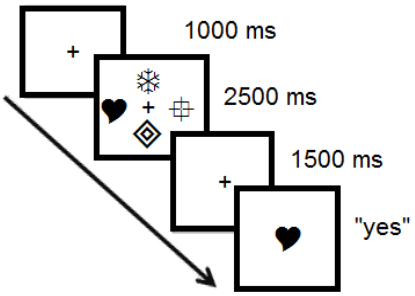
Procedure and Conditions in the Modified Flanker Task

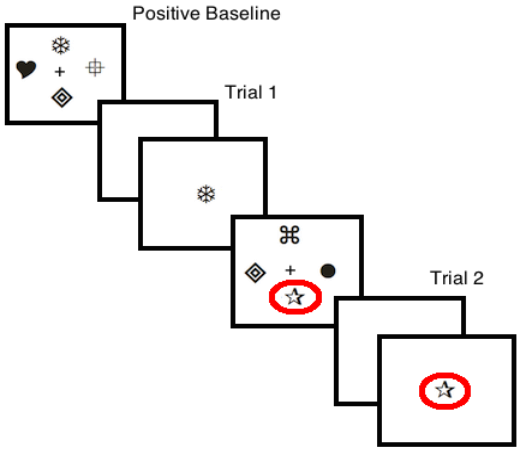


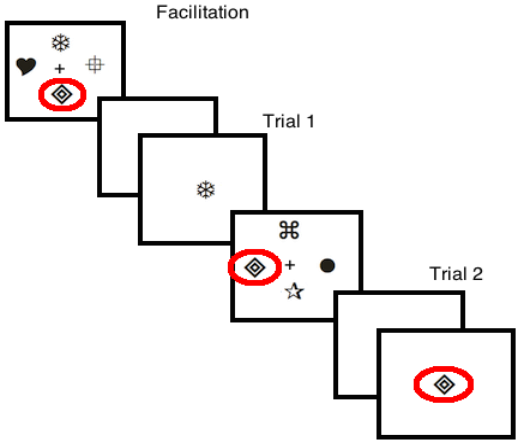


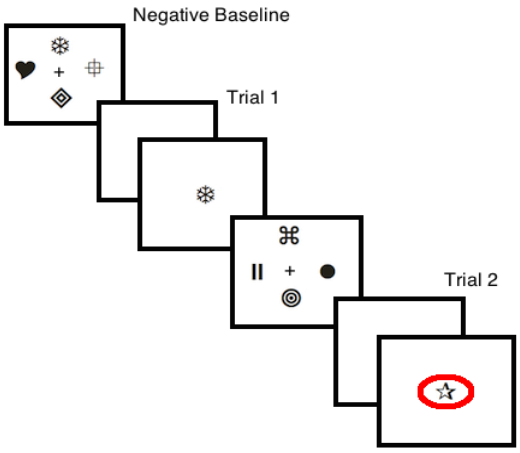
Appendix C

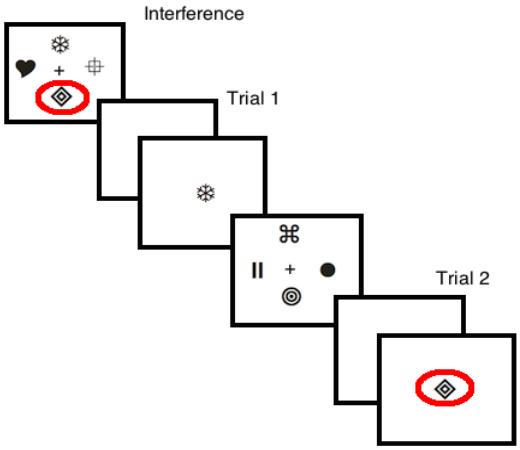
Procedure and Trial Types in the Recent Probe Task











Appendix D

Conditions in the Running Memory Procedure Task

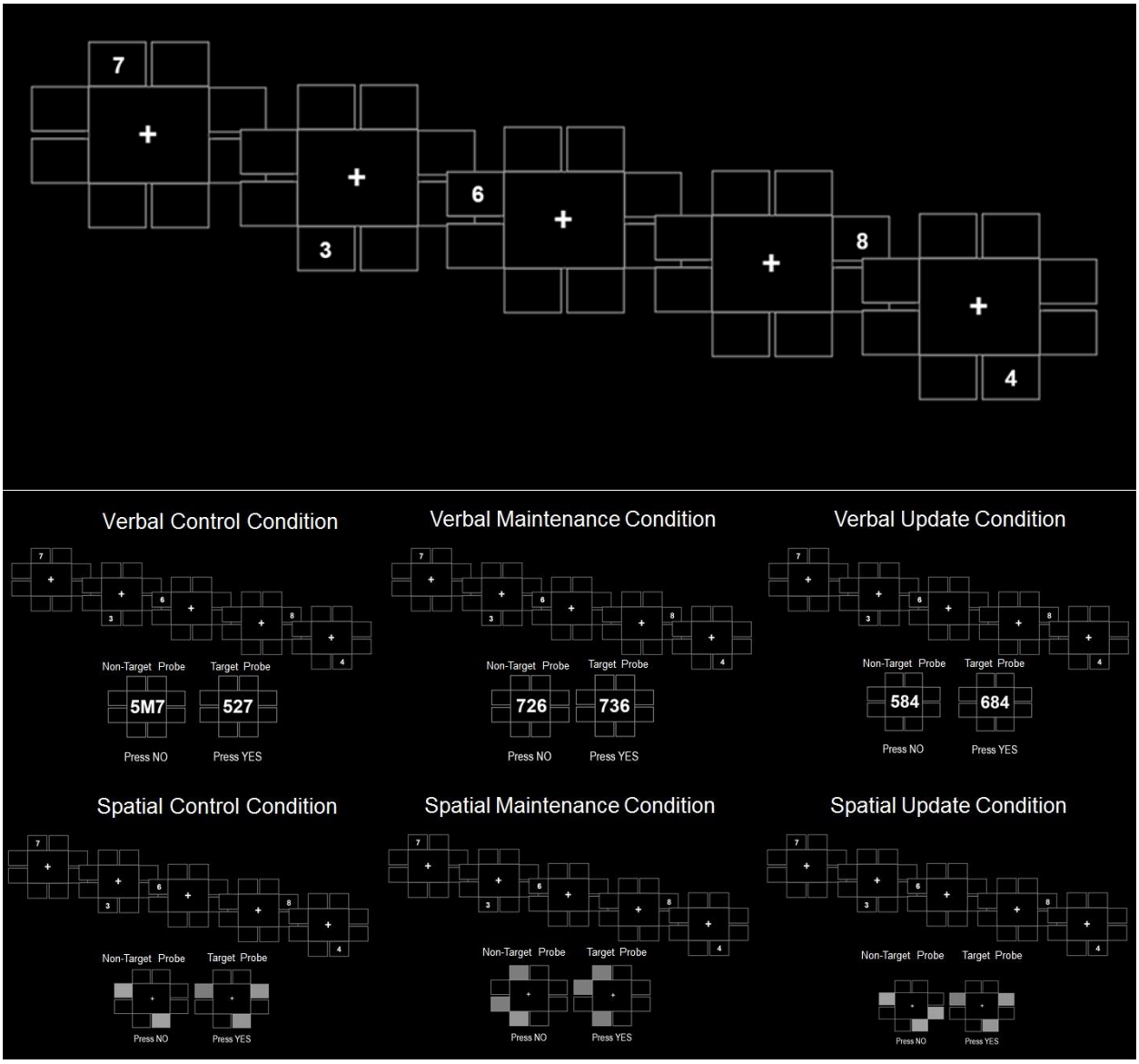


Image adapted from Watter et al. (2010).

Appendix E

Stimulus Timing in the Running Memory Procedure Task

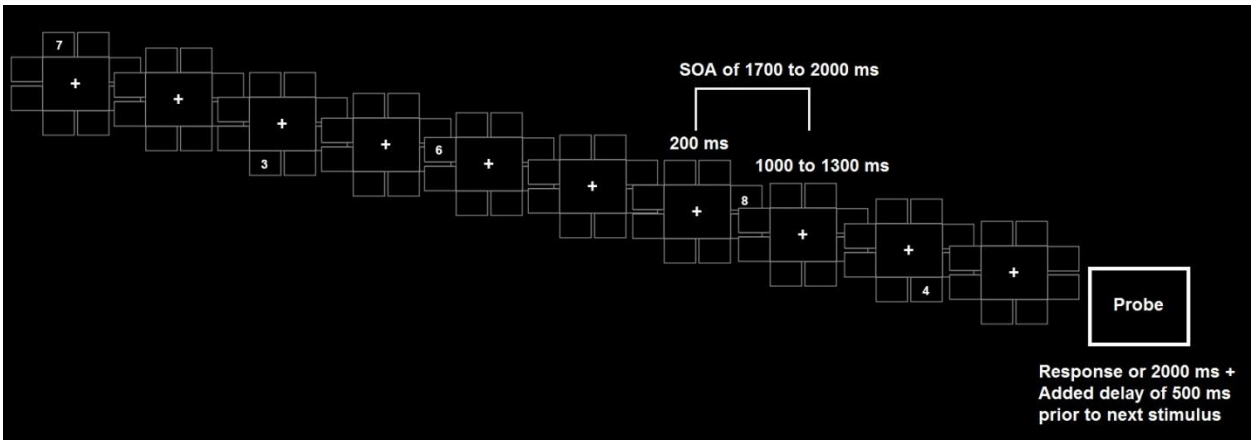


Image adapted from Watter et al. (2010).