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The Effects of Bilingualism on Memory and Brain Integrity Across the Adult Lifespan

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Dedication

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ABSTRACT OF THE DISSERTATION

The Effects of Bilingualism on Memory and Brain Integrity Across the Adult Lifespan

by

Alessandra Kaitlyn Macbeth

Doctor of Philosophy, Graduate Program in Psychology
University of California, Riverside, June 2020
Dr. Christine Chiarello, Chairperson

In the past two decades, there has been a surge of attention given to the study of bilingualism. Much of this interest has centered around trying to understand whether the continual act of selecting and controlling multiple languages can provide domain-general benefits to other aspects of cognition, particularly those that involve inhibitory processes. While most of this research has focused on testing bilinguals' abilities to suppress prepotent responses or ignore perceptual distractors, very little attention has been given to bilingual performance on tasks that involve inhibiting irrelevant memory traces in order to focus attentional resources on more relevant to-be-remembered information – otherwise known as resistance to proactive interference (PI). In addition, more recent research has suggested that being bilingual might provide cognitive preservation in the face of neural atrophy (cognitive reserve) or neural enhancement that maintains cognition (brain reserve). Therefore, the present study sought to determine whether being bilingual does in fact provide benefits and/or preservation to resistance to PI performance and brain structure in the regions important for resistance to PI abilities. Eighty-two younger and older adult participants, half of whom were English monolinguals and half were highly proficient Spanish-English bilinguals, participated in this study. They completed directed forgetting and release from PI tasks and underwent an MRI scan that captured indices of both cortical structure and white matter integrity. The results indicated that while bilinguals and monolinguals did not differ in their behavioral performance, the bilinguals displayed thinner cortex in resistance to PI-related regions (cognitive reserve) *and* showed significant positive relationships between white matter integrity and resistance to PI task performance (brain reserve). In addition, certain aspects of Spanish proficiency and use predicted better performance on the resistance to PI tasks among the bilinguals, indicating that knowing a second language does provide some protective effect to cognition. Importantly, this study is the first of its kind to demonstrate both cognitive reserve and brain reserve in different indices of brain structure within the same participants and shows that being bilingual supports important structural relationships between the brain regions necessary for inhibition, memory, and language.

Table of Contents

List of Tables

List of Figures

Chapter 1

Introduction

Investigating how to enhance memory performance across the lifespan is an important topic in psychology, since memory is one of the first cognitive processes to decline with increasing age (Hedden & Gabrieli, 2004). Training skills such as inhibition – the act of restraining a well-learned response or drawing attention away from irrelevant information to focus on pertinent task goals – may have a broader impact on memory ability, since successful remembering is contingent upon selective, intentional rehearsal of relevant information (Bjork, 1972). Even more ideal is a situation where individuals receive such inhibitory training out of necessity, in order to perform day-to-day tasks with ease and little mental conflict. One population that may fit these criteria are bilinguals, individuals who regularly use two or more languages (Grosjean, 1998). The primary aims of my research were to understand how bilingualism might affect certain aspects of memory performance, whether these potential benefits were present in both younger and older adults, and how the neural correlates of inhibitory control of memory might differ between bilinguals and monolinguals.

Inhibition in Bilinguals

Several studies demonstrate a “bilingual advantage” in cognitive processes that require executive function (see Bialystok, 2017 for a review). The premise is that a bilingual’s two languages are constantly and jointly active (Kroll, Dussias, Bice, & Perrotti, 2015); thus, bilinguals become adept at monitoring potential conflict and inhibiting the irrelevant language to achieve task goals (e.g., switching between languages) most effectively. If an inhibitory advantage is present in language control, these benefits might be domain-general and extend to nonlinguistic cognitive processes. Such benefits for inhibition have been evidenced in children (Martin-Rhee & Bialystok, 2008), young adults (Costa, Hernandez, & Sebastian-Galles, 2008) and middle-aged and older adults (Bialystok, Craik, Klein, & Viswanathan, 2004), on tasks such as the Simon task and Attentional Network Task (ANT).

However, several studies have suggested that, on the contrary, being bilingual does not afford cognitive advantages, particularly in executive function domains, and primarily among young adults. Hilchey and Klein (2011) reviewed a large literature examining whether a bilingual advantage exists for young adults on executive function tasks, distinguishing between studies that tested inhibition and those that looked at more general cognitive abilities, such as processing speed. They concluded there was little evidence for better inhibitory control (which they defined as smaller interference effects) among bilinguals, but stronger support for an advantage in global response times (bilinguals tend to outperform monolinguals by responding faster on both congruent and incongruent trials; Hilchey & Klein, 2011). Another group of young adult monolinguals and early bilinguals (second language acquired prior to age eight) were compared on performance on the Simon task, color-shape switching, the Flanker task, and an antisaccade task (Paap & Greenberg, 2013). No differences were found between these two groups on any of the tasks, for any dependent measure including global response times, switch costs, or interference effects. In addition, a study that compared Stroop task interference among both younger and older adults found no effect of bilingualism for either age group, though a general speed advantage did exist for the bilinguals (Kousaie & Phillips, 2012). Thus, many researchers have concluded that no bilingual advantage exists in any domain of executive processing, with some arguing that bilinguals might indeed recruit additional cognitive mechanisms as a function of managing two languages, but likely not to a large enough extent to generate group differences (Paap & Greenberg, 2013). It is also possible that executive control for language is in fact domain-specific, and bilingual advantages do not extend to non-language tasks.

More recent work examined a large sample of young adults (Von Bastian, Souza, & Gade, 2016) in which low, medium, and high proficiency early bilinguals had their performance compared on a variety of cognitive tasks that measured four constructs hypothesized to show bilingual benefits: inhibitory control (Hilchey & Klein, 2011), conflict monitoring (Costa, Hernandez, Costa-Faidella, & Sebastian-Galles, 2009), shifting (Bialystok, Craik, & Luk, 2012), and a generalized cognitive advantage (Kroll & Bialystok, 2013). Von Bastian and colleagues (2016) found no significant group differences across any of the four constructs, and they argue their results reflect a false-positive bias in the bilingualism literature as a function of the small sample sizes used in previous studies. However, since this study was performed in Switzerland, a country known for its multilingual environment, there is likely not much variability between a low and high-proficiency bilingual from this sample compared to two individuals from a country such as the United States. Additionally, no monolinguals took part in the study, so it is unclear as to whether any of the bilingual groups would have performed significantly better on any of the tasks than a monolingual might have.

It is important to note that the studies by Paap & Greenberg (2013) and Von Bastian et al. (2016) only examined young adults. It has been suggested elsewhere (Bialystok, 2017) that young adult monolinguals and bilinguals perform similarly on these tasks because college-aged adults are at their cognitive peak, and so effects of bilingualism tend to be washed out. Bialystok suggests that potential benefits of bilingualism are typically more prevalent in childhood or old age.

However, null effects have also been reported in studies comparing monolingual and bilingual children (Dick et al., 2018) and older adults (Papageorgiou, Bright, Tomas, & Filippi, 2019). As part of the Adolescent Brain and Cognitive Development (ABCD) Study, over 4,000 nine- and ten-year-old children were tested on flanker, stop-signal, and Dimensional Change Card Sort tasks to assess their inhibitory control and task-switching abilities. The authors found no differences between the monolingual and bilingual children on any of these tasks (Dick et al., 2018). Similarly, Papageorgiou and colleagues (2019) tested older monolinguals and bilinguals between the ages of 60 to 80 on a variety of cognitive tests and found no differences between the groups on any of the measures, including an inhibition task (the Simon task). The bilingual groups in both studies consistently used their non-English language, despite living in English-dominant countries such as the United States (Dick et al., 2018) and England (Papageorgiou et al., 2019), though neither study reported proficiency scores or ratings for the bilinguals' two languages. Therefore, it is difficult to assess how more or less proficiency in the non-English language might have affected cognitive outcomes for the bilingual participants.

As described above, there is a great deal of controversy over whether a bilingual inhibitory advantage truly exists. While the evidence for a lack of bilingual advantage is arguably convincing, there are several things to consider. First, most of these studies use language group as a dichotomous variable (bilingual or monolingual). An increasingly common approach is to treat bilingualism as a spectrum and consider cognitive outcomes as a function of continuous variables such as age of acquisition, length of immersion, or frequency of language use in different contexts (e.g., at home versus in social settings), to name a few (DeLuca, Rothman, Bialystok, & Pliatsikas, 2019a). Second, it is possible that although there are no evident behavioral differences between monolinguals and bilinguals, patterns of neural activity or brain structure might diverge, demonstrating that the two groups have unique ways of achieving the same cognitive outcomes. The Adaptive Control Hypothesis asserts that bilinguals recruit different brain regions based on individual differences in the context of language use (Green & Abutalebi, 2013), and as such, it is likely inappropriate to categorize all bilinguals under a single label (Antoniou, 2019).

Additionally, part of this debate stems from the cognitive tasks themselves, and the question of whether various executive function tasks actually involve inhibition. Friedman (2016) notes executive function paradigms often face the “task impurity problem”, meaning they measure additional cognitive processes besides the specific construct being tested. Even Bialystok, in her recent review, suggests that the advantage may not lie in inhibition per se, but in attentional control mechanisms (Bialystok, 2017). Of course, this does not rule out the role of inhibition altogether, since preventing irrelevant material from entering the focus of attention is vital for completing task-relevant goals. Finally, Valian (2015) notes that many cognitively challenging activities benefit executive function, and individual differences in the type and number of enriching experiences that people have can influence the extent to which bilingualism provides additional benefits to cognition.

The evidence is mixed regarding whether inhibition is enhanced among bilinguals, but one aspect that is not fully addressed in many of these studies is how the researchers are defining inhibition, and what type of inhibition is being measured in these tasks given to bilingual participants. In 2004, Friedman and Miyake published a paper that sought to separate different inhibition components. They identified what they considered to be the three main types of inhibition: prepotent response inhibition (the ability to suppress automatic responses, e.g., a stop-signal or Stroop task), resistance to distractor interference (the ability to ignore perceptual distractions in the external environment not relevant to the current task, e.g., a flanker task), and resistance to proactive interference (the ability to ignore previously learned information that has since become irrelevant to achieve task goals, e.g., a Brown-Peterson variant used by Kane & Engle, 2000). After performing a latent variable analysis, Friedman & Miyake (2004) found that prepotent response inhibition and resistance to distractor interference shared significant variance and seemed to measure the same inhibition construct, but resistance to proactive interference remained separable, sharing virtually no variance with the other variables (which Friedman and Miyake eventually combined into a single term: response/distractor inhibition). Another study combined a directed forgetting task (also considered a measure of resistance to proactive interference) and stop-signal task (measuring response/distractor inhibition) into a single task design, to test whether the two tasks tap into the same type of inhibition (Bissett, Nee, & Jonides, 2009). In this task, participants were shown a group of four letters, followed by the presentation of two of those letters, which they were supposed to forget. After a brief delay, a probe letter was shown, and participants had to identify whether this was one of the two letters from the original study set that was to-be-remembered. On about one-fifth of the trials, a stop-signal tone was presented, and participants were supposed to refrain from responding (Bissett et al., 2009). The authors' hypothesis was that if the two types of inhibition rely on the same processes, then stop-signal reaction times will vary as a function of probe type, such that responses requiring resistance to proactive interference (due to the presentation of a forget probe) will have longer stop-signal reaction times than responses that do not require proactive interference resolution (control probes). Ultimately, they found that the response/distractor inhibition and proactive interference tasks did not interact (stop-signal reaction times were the same for both forget and control probes), suggesting that they are dissociable inhibitory functions. These findings support the claim by Friedman and Miyake (2004) that resistance to proactive interference should be considered a separate and independent form of inhibition.

In considering how these two types of inhibition differ, it seems the key divergence between them is that resistance to proactive interference (henceforth abbreviated as PI) manages interference resulting from irrelevant information being held in *memory*, whereas the interference in response/distractor inhibition stems from lower-level *perceptual* processing of a stimulus array, and/or further deciding whether or not to initiate an action in response to the stimulus (Pettigrew & Martin, 2014). Up to this point, inhibition tasks typically studied in bilinguals include Simon, flanker, Stroop, and antisaccade tasks (Bialystok, 2017), the types of tasks that, by Friedman & Miyake's definition, are measuring response/distractor inhibition. However, only a few studies to date have examined resistance to PI performance in bilinguals versus monolinguals (Bialystok & Feng, 2009; Marton, Goral, Campanelli, Yoon, & Obler, 2017). In the work by Bialystok & Feng (2009), early bilingual and monolingual children and young adults performed a release from PI task. The release from PI task demonstrates that when trying to encode and retrieve information in memory, interference builds up across lists of similar items, but release from interference (and a subsequent increase in memory performance) occurs once dissimilar items are introduced (Wickens et al., 1963). In particular, changes in semantic content produce some of the largest release from PI effects (Wickens, 1970). In the paradigm presented by Bialystok and Feng, participants are sequentially presented with three lists that are all composed of words from the same category; after the presentation of each list, they are asked to recall as many words as possible from that particular list. The common finding is that as interference increases across lists due to the semantic similarity of the words being encoded, recall decreases. However, once a fourth list is presented with words from a new category, recall performance is restored to the level exhibited on List 1 (release from PI). Focusing on the young adults, since those results are the most relevant to the present study, the authors concluded that the pattern of PI buildup and release did not differ between the monolinguals and bilinguals (Bialystok & Feng, 2009). However, when differences in vocabulary were accounted for (the bilinguals in the study had significantly lower vocabulary scores than the monolinguals), the bilinguals showed a main effect, demonstrating a significant recall advantage over monolinguals across all four lists (Bialystok & Feng, 2009). These results suggest that future studies should control for vocabulary when comparing recall performance between bilinguals and monolinguals, particularly on memory tasks that utilize words as stimuli. Another recent study also compared a group of early, balanced bilinguals to monolingual young adults in their performance on various executive function tasks, one of which was a categorization task with a resistance to PI component (Marton et al., 2017). Marton and colleagues (2017) found that, although both groups showed a decline in performance in the proactive interference condition as compared to the baseline categorization condition, the decrease for monolinguals was significantly larger than the decline in bilingual performance. Taken together, these studies provide us with preliminary evidence to suggest that performance advantages in resistance to PI might exist among bilinguals who acquired a second language early in life. If early bilinguals possess superior attentional and inhibitory mechanisms as a function of constant language control, then these benefits might carry over into certain aspects of memory processing, particularly resistance to PI.

Inhibition in Older Adults

As adults get older, they begin to show a steady decline in inhibitory processes (Hasher & Zacks, 1988; Lustig, Hasher, & Zacks, 2007). In a definition of inhibition presented by Lustig and colleagues (2007), irrelevant information can either be prevented completely from entering the focus of attention (called “access”) or removed from one’s focus of attention post hoc (“deletion”). Weeks and Hasher (2018) suggest that older adults become worse at inhibitory processes because they experience an “attentional broadening” as they age. This occurs as a function of not being able to adequately filter relevant information from distracting information (a failure of the “deletion” process), which in turn can affect memory abilities such as resistance to PI, since older adults tend to be worse at discriminating which pieces of information to remember.

Consequently, resistance to PI performance has been measured in older adults to test this attentional broadening hypothesis. A study by Pettigrew & Martin (2014) administered a series of PI tasks (e.g., negative probes, cued recall, release from PI) to a sample of older adults and found that they demonstrated much larger interference effects than young adults across all three tasks. The authors concluded that their findings support the “hyperbinding” effect (Campbell, Hasher, & Thomas, 2010) such that older adults tend to bind extraneous or irrelevant information to items they should be remembering, resulting in greater interference at test. The notion of hyperbinding is complementary to attentional broadening; both ideas suggest that older adults fail to ignore irrelevant details, and thus remember information that is not useful or necessary for the goal they are trying to achieve. Thus, it seems that older adults’ declining resistance to PI is a function of irrelevant and relevant memory information being stored together, confounding the encoding process and making memory retrieval of particular words or details significantly more difficult.

As mentioned previously, directed forgetting tasks also fall under the umbrella of resistance to PI tasks, and these directed forgetting paradigms seem to be much more prevalent in the older adult literature. First created by Bjork (1972), participants are given a memory test during which they are cued to either remember or forget each word they have just encoded. Performance depends on how well one is able to recall “to-be-remembered” information, while also successfully inhibiting “to-be-forgotten” stimuli. In such tasks, older adults often remember more “to-be-forgotten” items than younger adults, since they struggle to inhibit previously learned but now irrelevant information (Weeks & Hasher, 2018; Zacks, Radvansky, & Hasher, 1996). A recent fMRI study (Campbell, Grady, Ng, & Hasher, 2012) gave both younger and older adults a visual 1-back task with objects, but on each object a word or random letter string was superimposed, which the participants were told to ignore. After completing the 1-back task, participants were given a stem completion task, in order to test their implicit memory for the words seen at study. Older adults completed the stems with significantly more “ignored” words from the study phase than younger adults (Campbell et al., 2012). While not a true directed forgetting task, the premise is similar – these findings demonstrate worse performance in older adults, since older adults were more susceptible to remembering information irrelevant to the task. Neurally, the older adults showed less functional connectivity during the task in a fronto-parietal network made up of cognitive control regions, suggesting that poorer task performance may be related to decreased coherence of a network important for successful forgetting (Campbell et al., 2012). The behavioral portion of these results was recently replicated by Weeks and Hasher (2018).

Another study that examined directed forgetting performance among both younger and older adults (Hogge, Adam, & Collette, 2008) gave participants a stem, and they either had to complete the stem using a word from the learning phase (could be a “remember” or “forget” word), or with a new word that had not been studied. This type of recognition paradigm sought to separate recollection from familiarity-based responses, and Hogge and colleagues (2008) ultimately concluded older adults produced more familiarity responses, coupled with poorer recollection. Since recollection is thought to involve cognitive control processes (Balota, Dolan, & Duchek, 2000; Davidson & Glisky, 2002), these results ultimately suggested an overall decline in attentional inhibition processes among aging individuals.

In addition, a recent meta-analysis examined aging and directed forgetting performance and concluded that the forgetting effect appears to be stronger in younger than in older adults, indicating that older adults are worse at forgetting no longer relevant information (Titz & Verhaeghen, 2010). There has been some debate in the literature over whether a list-method or item-method directed forgetting task is more sensitive to age effects – the results of the meta-analysis suggested that directed forgetting age effects are larger when the item-method version of the task is used, and when a recall format of the task is used rather than a recognition format (Titz & Verhaeghen, 2010; this finding has also been supported in prior work by Sego, Golding, and Gottlob, 2006). When considering why older adults might show poorer performance (e.g., remembering more to-be-forgotten words) on an item-method version of the task, Titz and Verhaeghen (2010) note that while both versions of the task rely on inhibition, the item-method induces forgetting at encoding, while the list-method relies more heavily on forgetting at retrieval; thus, failures of inhibition at encoding seem to be more prominent than failures of inhibition at retrieval among older adults (Hasher, Zacks, & May, 1999). Based on the evidence reviewed above, it appears that both release from PI and directed forgetting tasks are able to adequately capture the hyperbinding and attentional broadening mechanisms that older adults undergo, which leads to poorer inhibitory function and episodic memory performance with increasing age.

Resistance to PI and the Brain

Considering the findings presented thus far, it is clear that resistance to PI relies on an important inhibitory mechanism that seems to decline with increasing age but may be enhanced among bilingual individuals. However, what have not been discussed yet are the brain regions involved in resistance to PI tasks. Several studies have demonstrated that resistance to PI significantly activates regions in the frontal cortex – a PET study done by Jonides and colleagues was the first to find evidence suggesting that the inferior frontal gyrus (IFG), particularly the pars triangularis, was a crucial region for resolving interference (Jonides, Smith, Marshuetz, Koeppe, & Reuter-Lorenz, 1998). While the left IFG is typically implicated in language processing (Sakai, 2005), the right IFG is considered crucial for inhibitory processes (Aron, Robbins, & Poldrack, 2004; 2014). A follow-up study (Jonides, Marshuetz, Smith, & Reuter-Lorenz, 2000) compared younger and older adults, and found significantly less activity among the older adults in the left

IFG during the resistance to PI task.[1] In addition, less activity was correlated with larger interference effects, highlighting a potential neural correlate of the decline in resistance to PI performance among aging adults (Jonides et al., 2000).

Further research has corroborated these results; one study gave young adult participants a working memory variant of the directed forgetting task, and the researchers found that in addition to activation in the left IFG as a result of recalling probes that were to-be-forgotten (a response that indicates the inability to resist PI, since those words should have been forgotten), significant activation was also found in the bilateral middle frontal gyrus (MFG) and anterior cingulate cortex (ACC; Zhang, Leung, & Johnson, 2003). fMRI during a recent probes task also led to detection of greater activation of the ACC during conflict-heavy trials; this makes sense given the ACC's involvement in conflict monitoring (Nelson, Reuter-Lorenz, Sylvester, Jonides, & Smith, 2003). A study published a few years later (Badre & Wagner, 2005) also implicated the left ventrolateral prefrontal cortex (a region that often includes the IFG), the dorsolateral prefrontal cortex (dlPFC), fronto-polar cortex, and the hippocampus in proactive interference resolution. Jonides and Nee (2006) reviewed all of the studies presented thus far and concluded that resolving instances of proactive interference involves a broad network of prefrontal regions that are typically implicated in cognitive control processes. This suggestion was supported by follow-up work in which participants completed both recent probes and directed forgetting tasks while undergoing functional imaging (Nee, Jonides, & Berman,

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[1] In this study, resistance to PI was measured via a recent probes task, where a word or object that was once a memory target serves as a distractor item in later trials. Responses are more burdened by interference if the distractor "probe" was just shown recently, such as in the previously presented trial.

2007). The authors found that during both of these tasks, the IFG showed strong functional connectivity to the medial temporal lobe and right ACC, and the left ACC showed strong functional connectivity with the anterior PFC, again implying that these regions are essential for monitoring conflict and resolving interference. In addition, a study by Nelson and colleagues (2009) gave participants a recent probes task and a verb generation task and found peaks of activation in both the pars triangularis and the MFG during conditions that evoked larger amounts of proactive interference (Nelson, Reuter-Lorenz, Persson, Sylvester, & Jonides, 2009). Ultimately, over a decade of research into the neural mechanisms of PI resolution have identified three main structures, the IFG, MFG, and ACC, as the most active and involved during resistance to PI tasks.

While these studies all identified brain regions that showed increased BOLD responses relative to the rest of the brain during PI tasks, it is unclear whether structural differences exist in these regions between individuals that might perform differently on these tasks, such as younger and older adults. As discussed earlier, there is a great deal of behavioral evidence to suggest that older adults show poorer performance on resistance to PI tasks such as release from PI (e.g., Pettigrew & Martin, 2014) and directed forgetting (e.g., Hogge et al., 2008), and cross-sectional data suggests that the structure and integrity of frontal regions begin to decline from young adulthood throughout the remainder of the adult lifespan (Hedden & Gabrieli, 2004). The IFG, MFG, and ACC are noteworthy also in that not only have they been implicated in resistance to PI tasks, but in the bilingualism literature as well (Li, Legault, & Litcofsky, 2014), since bilinguals must often mediate conflict and interference between their two languages. As discussed in more detail in the following two sections, the bilingualism literature has documented structural differences between monolinguals and bilinguals in cognitive control regions. However, it is unclear whether some of these same regions might be associated with behavioral differences in memory inhibition. Therefore, determining whether structural distinctions between bilinguals and monolinguals that possibly result from unique language experience might also be related to disparities in performance on resistance to PI paradigms is an important step forward in the bilingualism field.

The Bilingual Brain – Young Adults

Besides identifying differences in brain structure between older and younger adults, another popular topic in recent years is whether the bilingual brain differs structurally from the monolingual brain, and several new studies suggest this is indeed the case. In young adult bilinguals, most studies tend to find larger brain structures (e.g., greater grey matter volume/density or cortical thickness) in the bilingual group. One region implicated in such studies is the inferior parietal lobe (IPL); both early and late bilingual young adults showed greater grey matter density than monolinguals, and proficiency in a second language was positively correlated with IPL density, suggesting greater mastery of a second language is related to greater cortical plasticity (Mechelli et al., 2004). The authors also found that age of acquisition (AoA) was negatively correlated with IPL density, which further corroborates their hypothesis since individuals with later AoA are generally less proficient in their L2. Other work by Felton and colleagues (2017) demonstrated that cortical thickness of the right ACC was greater in bilingual young adults (AoA varied from birth to 17 years) compared to monolinguals. Additional evidence showed flanker task performance was positively correlated with ACC volume among bilinguals only (Abutalebi et al., 2012), which suggests that the more refined, or "tuned", a bilingual's executive control is as a function of their second language experience, the more a bilingual brain might differ structurally from a monolingual brain. Another examination of cortical thickness (Klein et al., 2014) compared monolingual brains with brains of both simultaneous and late sequential bilinguals. An interesting pattern emerged – the left IFG showed greatest cortical thickness among the late sequential bilinguals, followed by thinner IFG cortex in the simultaneous bilinguals, and thinnest cortex in the monolinguals. The right IFG displayed the opposite pattern; monolinguals displayed the thickest cortex, with sequential bilinguals showing the thinnest cortex, and simultaneous bilinguals in the middle. Klein and colleagues (2014) suggested that learning a second language (L2) later in life is related to greater structural changes, making the brain structure of late L2 learners appear the most different from monolingual brains. While this appears contradictory to the findings in the IPL by Mechelli and colleagues (2004), it is possible that the structure of certain brain regions may not always change in parallel (e.g., one region may become larger or thicker with more exposure to a second language, while another might become smaller or thinner). Additionally, the former set of findings measured IPL density, while the latter study by Klein et al. (2014) studied cortical thickness. It is possible that while early life experiences have a greater influence on density or volume, the plasticity of cortical thickness might be influenced more by experiences that occur post-childhood.

This interpretation by Klein et al. (2014) is in line with the cognitive training literature (see Lovden et al., 2013 for a review), which posits that intensive learning of a new skill will induce structural changes in regions specific to the skill being attained. Studies examining intensive second language learning have demonstrated findings in accordance with this hypothesis, with structural changes including increases in grey matter density in the left IFG and anterior temporal lobe after five months of L2 immersion (Stein et al., 2012), and cortical thickness increases in the left IFG, MFG, and superior temporal gyrus (STG), coupled with hippocampal volume increases over a three-month period of intensive second language learning (Martensson et al., 2012). Thus, it seems probable that being immersed in a second language as a young adult can induce structural brain changes, at least for the duration in which the language is actively being learned and used.

While the majority of studies examining grey matter in young adult bilinguals and monolinguals show greater indices of grey matter (e.g., volume or cortical thickness) among the bilinguals, a few studies have shown the opposite pattern of results. As previously mentioned, the study by Klein and colleagues (2014) showed greater cortical thickness in the right IFG for monolinguals compared to bilinguals. Another recent study examining the insula, a deep cortical region important for speech processing, found that thickness of the left anterior insula significantly predicted novel speech sound learning in bilinguals only, and interestingly, thinner insular cortex was related to more successful learning (Rodriguez, Archila-Suerte, Vaughn, Chiarello, & Hernandez, 2018). The authors suggest that thinner cortex might be a sign of a more efficient or streamlined neural mechanism supporting the cognitive processes involved in speech comprehension. Therefore, while we often associate “bigger” with “better,” this might not always be the case when it comes to brain structure.

Differences between bilinguals and monolingual young adults in subcortical brain structures have been examined as well, although this is a fairly new area of research. Burgaleta and colleagues (2016) determined that the bilateral putamen and thalamus both showed “expansion” in simultaneous bilinguals compared to monolinguals, in addition to expansions in the right caudate and left globus pallidus. These findings provide evidence for an intricate network of subcortical brain regions involved in articulatory processing, resulting from a more complex phonological system due to a wider range of speech sounds that the bilingual must learn and access (Burgaleta, Sanjuan, Ventura-Campos, Sebastian-Galles, & Avila, 2016). Another study that looked at subcortical changes compared late sequential bilinguals immersed in their L2 to monolinguals and found significant expansions in the bilateral putamen and globus pallidus, as well as the right thalamus (Pliatsikas, DeLuca, Moschopoulou, & Saddy, 2017). Both studies demonstrated larger subcortical structures in the bilinguals compared to the monolinguals, although whether the changes were bilateral or lateralized to one hemisphere seemed to depend on whether the L2 was acquired early or later in life. Another longitudinal study that scanned bilingual participants twice, three years apart, found that the additional time immersed in the L2 resulted in significant reshaping of the caudate, amygdala, and hippocampus (DeLuca, Rothman, & Pliatsikas, 2019b). Although there was no monolingual comparison group, the findings suggest that the brains of bilinguals continue to change in step with how language use changes over time, as well.

Many of the bilingualism studies that have searched for structural differences between monolingual and bilingual brains have focused on grey matter, but bilingualism also seems to play a role in influencing white matter. When studying white matter integrity, researchers typically refer to its diffusion properties, or how effectively water moves through the axon fibers. The most common metric used to quantify diffusion in white matter is fractional anisotropy (FA). FA is a value between 0 and 1, with a higher value indicating greater directionality of diffusion (Madden et al., 2012). Therefore, the higher FA in a given white matter tract, the more structurally intact that tract is, since the water is predominantly diffusing in a single direction. Other diffusion metrics commonly referred to in the white matter literature include axial diffusivity (AD) or diffusion along the primary axis of the tract, radial diffusivity (RD) or diffusion along the secondary (perpendicular) axis, and mean diffusivity (MD), the average of AD and RD. Higher RD or MD typically implies that diffusion in a particular tract is more isotropic – this means that water is diffusing in all directions and structural integrity of the tract is low, due to changes such as demyelination or other axonal pathology (Madden et al., 2012).

While the evidence for cortical enhancement in young adult bilinguals is somewhat convincing, the white matter data are a bit more convoluted. A recent study that compared monolinguals and late bilinguals found higher fractional anisotropy (FA) among the bilinguals in the corpus callosum, and this greater white matter integrity extended bilaterally to the inferior fronto-occipital fasciculus (IFOF), superior longitudinal fasciculus (SLF) and uncinate fasciculus (UF; Pliatsikas, Moschopoulou, & Saddy, 2015). It is possible that whether bilinguals had early or late exposure to their L2 may affect which white matter tracts undergo changes; a recent study found that early L2 exposure was related to increased FA in the arcuate fasciculus, whereas late L2 learning was related to lower MD in the IFOF (Hamalainen, Sairanen, Leminen, & Lehtonen, 2017). Another recent study found that higher FA in the right forceps minor and right anterior thalamic radiation predicted quicker reaction times in Chinese-English bilinguals when they performed a Stroop task in each of their languages, for both congruent and incongruent trials (Mamiya, Richards, & Kuhl, 2018). The forceps minor is a commissural tract that connects homologous parts of the anterior frontal lobes (Fabri et al., 2014), and the anterior thalamic radiation connects the thalamus to regions in the prefrontal cortex such as the ACC and DLPFC (Shibata & Naito, 2005). Taken together, the authors suggest that their results show that greater integrity in these two tracts is correlated with greater attentional control.

White matter alterations also appear to be evident when learning a second language. Studies that examined white matter changes in learners of an L2 found converging evidence, with participants showing an increase in FA and decrease in RD in tracts underlying language regions such as the pars triangularis (part of the IFG) and STG, in addition to the genu of the corpus callosum (Schlegel, Rudelson, & Tse, 2012), and greater FA in the white matter underlying the right pars opercularis (another portion of the IFG; Hosoda et al., 2013).

These findings provide evidence for increased white matter integrity in bilinguals; however, results presented by Singh and colleagues (2017) tell a different story. They compared white matter indices of young adult early bilinguals and monolinguals and found reduced FA among the bilinguals in the anterior thalamic radiation and the right IFOF, in addition to increased RD, AD, and MD in the right SLF. The authors suggest that more isotropic diffusivity is not necessarily a negative characteristic of white matter, hypothesizing that axon diameter in these regions might be increasing and myelination is stretched and sparser as a function of exposure to two languages (Singh et al., 2017). They suggest this "neuroplasticity" is generated by the cognitive load resulting from use of both languages, but do not suggest these white matter traits are negatively impacting the bilingual brain. However, the general consensus is that anisotropic diffusion of water along white matter fiber tracts constitutes greater integrity than water movement that is isotropic; therefore, the interpretation by Singh et al. (2017) must be taken with great caution. Another possible explanation is that the highly aligned tracts of bilinguals are crossing more than those of the monolinguals, contributing to the appearance of isotropic water movement, and thus lower FA and higher MD in these regions.

Another study also documented less white matter integrity for bilingual young adults compared to monolinguals. Cummine and Boliek (2013) found that English-speaking monolinguals had significantly greater FA than Chinese-English early sequential bilinguals in the right IFOF and bilateral anterior thalamic radiation. Conversely, there were no regions where bilinguals showed higher FA than the monolinguals. The authors suggest that the perceived "benefits" for bilinguals with regard to white matter integrity appear to be more prominent among older adults (which will be elaborated on in the following section) and for late bilinguals compared to early bilinguals. While it is clear that bilingualism induces brain changes, we still do not fully understand the mechanisms that cause such alterations, and whether "larger" structures are necessarily "better" in all cases, for either white or grey matter.

The Bilingual Brain – Older Adults

Since structural differences have been evidenced in the young adult population, might a reasonable assumption be that they persist across the lifespan? Several studies support this hypothesis. Abutalebi and colleagues found significantly greater grey matter volume in the left temporal pole (Abutalebi et al., 2014) and in the IPL (Abutalebi et al., 2015a) among bilingual older adults. In these two cross-sectional studies, age effects were observed for monolinguals, indicating more atrophy of grey matter volume (GMV) with older age, but this same pattern was not observed among the bilinguals. These results imply bilinguals maintain cortical integrity into old age, and this is consistent with the concept of brain reserve, which states cognition will remain intact providing the brain's structural integrity is also preserved and does not decline past a fixed threshold (Stern, 2009).

This notion of brain reserve has been supported by more recent research that found systematically higher volume in the IFG and IPL of a large-scale sample (N = 399) of bilinguals compared to monolinguals (Heim et al., 2019). The majority of participants in the sample were between the ages of 55-85, however some structural data was included for participants between the ages of 25-54 as well. Interestingly, the authors note that GMV differences in these regions were strongly modulated by age, such that the difference in IFG volume between the bilingual and monolingual groups disappears around age 60, but the difference in IPL volume does not diminish until age 80 or older. Evidence for a protective effect in the posterior, rather than anterior, regions of the language network are in line with the Bilingual Anterior-to-Posterior and Subcortical Shift model proposed by Grundy and colleagues (2017). Their proposal suggests that bilinguals rely on posterior brain regions more than anterior regions as they age; since cognitive decline in older adults is often attributed to the diminishing efficiency of frontal regions, this could be one explanation as to why bilinguals show cognitive decline later than monolinguals (Grundy, Anderson, & Bialystok, 2017).

Other work by Abutalebi's research team also suggests that although there are age-related volume decreases in the dorsolateral prefrontal cortex (dlPFC) for both monolinguals and bilinguals, poorer cognitive performance is associated with this decline only among the monolinguals, with no relationship present for bilinguals (Abutalebi et al., 2015b). Although both groups in this experiment did experience structural deterioration, the bilinguals' cognitive performance remained intact. Interestingly, bilinguals also showed greater GMV in the ACC (Abutalebi et al., 2015b), another example of brain reserve. Taken together, these findings may imply that certain brain regions are subject to a slower rate of decline among bilingual older adults, and while structural loss may be inevitable in other regions such as frontal cortex (Hedden & Gabrieli, 2004), cognition seems to be preserved as a function of using two languages throughout the lifespan.

Again, like in the younger adults, the white matter evidence is a bit more mixed. An examination of white matter integrity in lifelong bilinguals showed significantly greater FA in the corpus callosum compared to monolinguals, and this increased integrity extended bilaterally to the SLF, the right IFOF, and right UF (Luk, Bialystok, Craik, & Grady, 2011a), consistent with the brain reserve hypothesis. In addition, monolingual older adults had significantly higher RD in the corpus callosum than the bilinguals, suggesting that white matter integrity is poorer for individuals who do not know a second language (Luk et al., 2011a). However, a different study by Gold and colleagues (2013) found that their sample of bilinguals had lower FA in the IFOF, inferior longitudinal fasciculus (ILF), corpus callosum, and fornix than the monolinguals, plus higher RD in the IFOF and corpus callosum. The authors suggest that their sample of older adults may have been more susceptible to Alzheimer's disease pathology compared to the sample studied by Luk and colleagues (2011a), which might have contributed to the divergent findings. An alternative explanation evokes the notion of cognitive reserve. The idea is that some life experiences, such as higher levels of education or a more intellectually demanding occupation, may preserve cognition in the face of brain atrophy (Stern, 2009). The bilinguals and monolinguals in Gold et al.'s study were matched for several factors typically used as measures of cognitive reserve, such as years of education and IQ. One of the primary purposes of the study by Gold et al. (2013) was to determine whether bilingual status could also be presented as a factor of cognitive reserve, and the results provide convincing evidence for this hypothesis, by effectively showing that when older bilingual participants are cognitively equivalent to monolinguals, their brain atrophy is much more extreme – a textbook example of cognitive reserve.

Additional studies have examined cognitive reserve in bilinguals and monolinguals who are beginning to demonstrate symptoms of mild cognitive impairment (MCI) or Alzheimer's disease. In general, research shows that bilinguals tend to exhibit symptoms of dementia approximately 4-5 years later than monolinguals do (Alladi et al., 2013; Bialystok, Craik, & Freedman, 2007; Craik, Bialystok, & Freedman, 2010). A few recent studies have looked at brain structure in such populations once they start to decline cognitively. The first known study to do so found that lifelong bilinguals with Alzheimer's showed much greater brain atrophy in medial temporal regions than monolingual Alzheimer's patients who had been matched to the bilinguals on cognition and education variables (Schweizer, Ware, Fischer, Craik, & Bialystok, 2012). Another recent examination by Duncan and colleagues (2018) compared cortical thickness and grey matter density of brain regions important for memory and for cognitive control in lifelong multilinguals (approximately half were bilingual, and the other half spoke three or more languages) and monolinguals who either had been diagnosed with MCI or Alzheimer's disease. Both the MCI and Alzheimer's multilinguals showed thicker cortex and increased grey matter density in cognitive control regions such as the IFG and MFG than their matched monolingual counterparts, providing evidence for brain reserve in the multilingual sample. However, while the multilinguals of both disease types showed greater hippocampal density than the monolinguals, in other memory regions such as the bilateral parahippocampal gyri and rhinal sulci, grey matter density was greater in the

MCI multilinguals compared to the MCI monolinguals, but higher in the Alzheimer's monolinguals compared to the Alzheimer's multilinguals. The hippocampal findings again support the brain reserve hypothesis, but the differences in the other medial temporal regions are best explained by a cognitive reserve perspective.

These results are important in that they are the first to demonstrate support for both brain and cognitive reserve within the same study. While most past research has supported brain reserve or cognitive reserve in accounting for brain differences between bilinguals and monolinguals, this study demonstrates that the two can coexist. Regions heavily involved in memory processing atrophy more in multilinguals that have progressed to Alzheimer's compared to monolinguals with Alzheimer's (when their cognitive performance is matched), but regions that play a larger role in language and cognitive control processes do not seem to be affected by the same disease progression. Instead, these regions remain more structurally intact in the multilingual group, demonstrating that the bilingual brain can exhibit plasticity in numerous ways and along many different time courses, depending on the regions of interest.

Taken together, the findings suggest that structural differences between bilinguals and monolinguals in both grey and white matter are present throughout the adult lifespan, though only a few studies demonstrate replications for particular brain regions across age groups. In white matter, bilinguals showed increased FA in the left IFOF and the corpus callosum, in samples of younger (Pliatsikas et al., 2015) and older adults (Luk et al., 2011a). The corpus callosum is important for interhemispheric interaction and has been implicated in executive functioning; it is possible that it plays a role in switching abilities, although these structure-function correlates are not entirely understood (Pliatsikas et al., 2015). The IFOF has been demonstrated to be important for language processing of semantic information in particular (Mohades et al. 2012; Pliatsikas et al., 2015). However, among studies examining grey matter alterations, few studies find bilingual versus monolingual differences in the same regions of interest; in fact, of the studies considered earlier, the only cortical region that was shown to have greater grey matter volume among bilinguals in more than one study is the IPL (Mechelli et al., 2004; Abutalebi et al., 2015a), an important language processing and cognitive control region. In addition, there appears to be a lack of consistency in trying to replicate findings with a particular imaging modality. Within each age group (younger and older adults), there are only a few studies examining grey matter or white matter, and very rarely are multiple modalities (e.g., structural MRI, DTI) used within the same study (see Gold et al., 2013, for the only example to date). Using multiple methods of imaging within the same group of individuals can be useful in helping researchers determine the extent to which grey and white matter changes are related.

It is also possible that discrepancies exist among these structural studies because they are capturing the brains of individuals with differing amounts of experience with their second language. Pliatsikas (2019) recently proposed the Dynamic Restructuring Model, which suggests that differences in grey matter between bilinguals and monolinguals are more prevalent at early stages of exposure to a second language, but once bilinguals become highly immersed, there is a pruning of those anterior connections and greater reliance on subcortical brain structures such as the caudate nucleus, as well as increased integrity of white matter tracts implicated in language processing. Continual exposure to both languages is also a critical factor; if a bilingual is highly proficient in both languages, but if not continuously exposed to both, then changes in subcortical structures or white matter may not be evident.

It is also surprising that the majority of these neuroimaging studies have not included cognitive tasks in their experimental paradigms, leaving readers with little means of assessing how such brain differences might relate to behavioral disparities. A common conclusion among these studies is that bilingual brains differ in certain structural aspects from monolingual brains because bilinguals routinely employ greater levels of executive control, to manage the continuous and active nature of their two languages. However, from the present literature there is no way to determine whether behavior is associated with the structural changes that are thought to be due to bilingualism. Some of the studies, particularly those involving older adults, do give participants a series of neuropsychological tests, which sometimes will include an executive control task (e.g., the Stroop task; Luk et al., 2011a), but in this case the authors are using these tasks to match the groups rather than to explore individual differences in task performance.

Bilingual Experience Factors

Comparison of results across studies is also made difficult by the fact that subject-level variables, such as language proficiency, age of acquisition (AoA), length of immersion, and context and frequency of language use often differ between samples and may have an influence upon what structural changes are evident from study to study.

Among older adults, AoA does not seem to have much of a relationship with structural change; Abutalebi and colleagues (2015a) suggest that proficiency is instead a better predictor of structural alteration, such that individuals who are more fluent in their second language in old age are likely to use that language more often than individuals who are not as proficient (in line with the Dynamic Restructuring Model; Pliatsikas, 2019). Greater frequency of use may subsequently allow for the maintenance or enhancement of structure. Further, neuroimaging studies comparing bilinguals and monolinguals have never before examined younger and older adults together in a cross-sectional dataset; such a comparison will be implemented in the present study.

Recently, there has also been a movement towards viewing language abilities as a continuous variable (e.g., "extent" of bilingualism) as opposed to a dichotomous one (e.g., bilingual versus monolingual). There are many individual differences that exist among bilinguals, and a call for greater sensitivity to these differences has been supported by several groups (DeLuca et al., 2019a; DeLuca et al., 2019b; Tabori, Mech, & Atagi, 2018). As such, I planned to conduct my analyses in two ways, if feasible: first, via a traditional comparison of monolingual and bilingual groups, and second, if I had enough variability of language experience within my sample, using regression models to determine how the extent of bilingualism or monolingualism may affect memory performance or brain structure.

Motivation for the Present Study

The original contributions of my research are threefold. The first goal was to demonstrate that the inhibitory benefits bilingualism may provide can have exciting implications for memory performance; to date, memory processing has been given little attention in the bilingualism research community. Specifically, little research has been done examining whether or not bilinguals demonstrate any benefits in resistance to PI, a measure of inhibitory and attentional control that acts on memory information. Since bilinguals have been shown to exhibit advantages on language control tasks, this benefit could be domain-general, and might extend to episodic memory abilities that also rely on inhibition and attention. I also wanted to test whether resistance to PI and response/distractor inhibition (Friedman and Miyake, 2004) are truly separable constructs, specifically among bilinguals. Therefore, I included a flanker task as part of my experimental protocol in order to determine whether inhibitory effects that may be evident in bilinguals are uniquely tuned for memory processes versus perceptual inhibition. Second, I investigated whether being bilingual aided in the preservation of memory abilities among older adults. For example, older adults tend to perform more poorly on resistance to PI tasks compared to young adults, but does being bilingual moderate this relationship? Another key issue is that several individual differences exist among bilinguals, such as the age at which they acquired their first language, how proficient they are in each language, and how often they use each language, and these variables might be further affected by their age (e.g., someone who is retired might have used English frequently in the workplace, but now just speaks Spanish in the home the majority of the time). It is important to determine which of these bilingual characteristics has the greatest impact upon both behavioral performance and structural differences. Finally, I explored whether bilingualism induced changes in brain structure, particularly in key regions important for inhibition and memory processes. There is some evidence to support a positive association between bilingualism and brain preservation (among older adults) or enhancement (in younger adults), but very few studies to date (Abutalebi et al., 2012; Abutalebi et al., 2015b), have actually examined the relationship between structural differences and cognitive performance within the same group of participants. I examined both younger and older adult bilinguals and monolinguals; no prior studies have compared all four of these groups of participants within a single experimental paradigm.

To answer these questions, a combination of behavioral measures and multimodal structural neuroimaging was used. Participants completed two paradigms that induce proactive interference: a release from PI task and an item-method directed forgetting task, as well as a flanker task to measure response/distractor inhibition. Performance of younger and older adults was compared, but an additional comparison was made between bilinguals and monolinguals *within* each age group. In addition, brain structure was compared between the four participant groups (monolingual and bilingual younger adults, and monolingual and bilingual older adults), using surface-based measures of volume and thickness of the cortex, volume measures of particular subcortical structures and the corpus callosum, and diffusion tensor imaging (DTI) of underlying white matter tracts. Based on the evidence discussed above, studying how bilingualism might affect memory ability and brain structures associated with the inhibition of memory in the aging population is a novel pursuit, and one that will provide exciting new insights into how being a lifelong bilingual can positively impact both brain and behavior.

Predictions for the older adults were rooted in the theoretical principles of brain reserve and cognitive reserve. If my findings were consistent with brain reserve, I would expect that behaviorally, the older adults would generally do worse overall on the resistance to PI tasks than the young adults (consistent with prior studies such as Pettigrew & Martin, 2014), but bilingual status and age would interact such that older adult bilinguals and young adults show a performance advantage compared to older adult monolinguals. The explicit memory tasks used in the present study are more frontally-mediated (Jonides & Nee, 2006), and cross-sectional research of normal aging shows that frontal brain regions atrophy steadily across the adult lifespan (Hedden & Gabrieli, 2004); however, I would expect preservation of these brain regions (brain reserve) in the older bilinguals, allowing their behavioral performance to remain intact and comparable to the young adults.

Additionally, I would expect that the older adult bilinguals would show greater GMV and cortical thickness in cognitive control regions (ACC, IFG, MFG) compared to the older monolinguals. These regions in particular are important for executive function, particularly resistance to PI (Jonides & Nee, 2006) and have been shown to differ between bilinguals and monolinguals in past studies (Abutalebi et al., 2015b, Felton et al., 2017, Klein et al., 2014, Martensson et al., 2012). In addition, white matter integrity in tracts underlying frontal memory regions (cingulum, SLF) as well as in tracts connecting the two hemispheres (e.g., the corpus callosum) should be greater in older bilinguals compared to older monolinguals (supported by past studies such as Luk et al., 2011a; Pliatsikas et al., 2015).

On the other hand, if my data supported the cognitive reserve hypothesis, then I would expect to see comparable behavioral performance on my resistance to PI tasks between my two older adult groups (with both groups performing more poorly than the younger adults), coupled with reduced structural integrity within the grey and white matter regions of interest specified previously, among the older bilinguals only. As mentioned previously, the hallmark characteristics of cognitive reserve include brain atrophy coupled with intact cognitive performance (Stern, 2009); if this is the pattern I see within my own data, I might conclude that lifelong bilingualism has afforded these older adults a cognitive mechanism by which to maintain behavioral performance, despite evidence of neural deterioration. Of course, the cognitive reserve theory suggests that the groups being compared are matched with regard to neuropsychological performance, so this would be something to consider in my own sample.

With regard to the young adults, I would not expect to see any differences in brain structure between the bilinguals and monolinguals. This prediction is based on the tenets of the Dynamic Restructuring Model (Pliatsikas, 2019), which suggest that cortical grey matter changes are most prominent among bilinguals with late exposure to a second language, and those who are still mastering the language. Since I expected that all of my young adult bilinguals would be either simultaneous or early sequential bilinguals with immersive language experience throughout their lives thus far, I hypothesized that any cortical changes that had occurred previously in the bilinguals had since renormalized (Pliatsikas, 2019). Additionally, I did not expect to find behavioral differences between monolingual and bilingual younger adults, since they should all be performing at their cognitive peak (Bialystok, 2017).

In addition, I expected that variables characterizing the bilingual experience (AoA, frequency of use, and proficiency) should each relate to memory performance in bilinguals across the two age groups; however, I predicted proficiency would show the strongest correlation with resistance to PI memory ability, since vocabulary knowledge was an important variable moderating release from PI performance in prior research (Bialystok & Feng, 2009).

Further, I also chose to conduct a few exploratory analyses, given my interest in memory performance and brain regions implicated in memory processing. I suggested that greater volume in the hippocampus may be present in the older adult bilinguals compared to monolinguals (as a function of brain reserve), whereas no difference may exist between the two groups of young adults, given that hippocampal decline does not generally begin until age 60-65 (Hedden & Gabrieli, 2004). I also examined group differences in a few additional white matter tracts of interest, the UF and ILF, as these bundles connect frontal to temporal brain structures (Jellison et al., 2004), and it was possible that bilinguals might show greater integrity along these tracts in order to support better memory performance.

Ultimately, the neural and cognitive changes that take place as a function of learning a second language are anything but static, and my goal was to connect these disparate findings into a cohesive understanding of how the bilingual mind and brain may provide advantages for resistance to PI performance in both young and older adulthood.

Chapter 2

Method

Participants

One hundred three individuals were tested as part of the present study. Of these participants, 54 were young adults (17 male) between the ages of 18 and 30 ($M = 20.48$ years) and 49 were older adults (17 male) between the ages of 55 and 85 ($M = 68.86$ years). Among the younger adults, 28 were monolingual English speakers, and 26 were Spanish-English bilinguals. Of the older adults, 24 were monolingual English speakers, and 25 were Spanish-English bilinguals.

Only a subsample of these participants completed the MRI scanning procedure and had usable MRI data in addition to the behavioral testing: 50 young adults (25 bilingual) and 37 older adults (16 bilingual). Further, of this sample, the monolingual and bilingual older adults differed significantly in terms of age; monolinguals ($M = 72.38$ years) were older than bilinguals ($M = 66.75$ years), $t(35) = 2.52$, $p = 0.02$. Therefore, in order to correct the age confound and keep sample size across the older adult groups equivalent, 16 monolinguals were age-matched to the 16 bilinguals with valid MRI data. This resulted in a final sample of 82 participants, 50 young adults and 32 older adults, that was used for all subsequent behavioral and imaging analysis. The younger and older adults differed significantly with regard to age, $t(80) = 51.10$, $p < .001$, but the bilinguals and monolinguals within each age group did not. Average ages and age ranges for each sample can be found in Table 1.

Table 1.
Sample characteristics for the final subset of participants used for analysis.

	N (Male)	Age (*SD*)	*t*-value	Age Range
Younger Adults				
Monolingual	25 (9)	20.1 (2.3)	0.82	18-28
Bilingual	25 (7)	20.6 (1.8)		18-24
Older Adults				
Monolingual	16 (4)	70.0 (4.5)	1.53	63-79
Bilingual	16 (6)	66.8 (7.2)		58-84

Bilingual status was initially assessed during an eligibility screening prior to testing. Participants were classified as monolingual if they rated their English proficiency as "Advanced" or "Native-like," and either reported that they knew no other languages or their proficiency in a second language was "Basic/Beginner." Participants were classified as bilingual if they rated themselves as having "Advanced" or "Native-like" proficiency in both English and Spanish, particularly for speaking and understanding each language. Participants' bilingual status was further assessed at the time of testing via a language history questionnaire, which will be discussed in more detail below.

All participants were right-handed (as measured by the Edinburgh Handedness Inventory; Oldfield, 1971), had normal or corrected-to-normal vision, and no history of any brain-related disease or injury. Younger adults were recruited from introductory psychology classes at UC Riverside and the surrounding community. Older adults were recruited from UC Riverside's lifespan database and the surrounding community.

Materials and Procedure

Participants came to the UC Riverside campus for two, two-hour testing sessions. In the first session, participants completed a series of behavioral tasks and questionnaires on a computer, and in the second session, all participants underwent a 30-minute structural MRI scan and completed an additional hour of behavioral testing on a computer. Sessions 1 and 2 were administered anywhere between 0 (meaning they completed both sessions in the same day) and 71 days apart (*M* = 11.51 days). The behavioral tasks administered in each session are described below, followed by the imaging parameters for the scan.

Screening. Prior to coming to campus, all participants underwent a thorough screening process, either over the phone or in-person, to determine whether they were eligible for the study. The screening asked questions about age, handedness, bilingual status, health history, and imaging contraindications. In addition, potential participants who were screened over the phone completed most of the Montreal Cognitive Assessment (MoCA v. 7.1, Nasreddine et al., 2005), except for the visuospatial/executive function tasks, naming task, and the last two orientation questions (place and city). If potential participants were screened in person, they completed the entire MoCA. If participants were determined to be eligible based on their answers to the screening questions and scores on the MoCA (at least 14 out of 20 for the partial MoCA or 21 out of 30 for the full MoCA), they were scheduled for testing. None of the participants received a MoCA score lower than 22 out of 30.

Session 1. During the first testing session, participants were consented and finished the remainder of the MoCA if they had completed their screening over the phone. Afterwards, participants completed a series of tasks including letter fluency, directed forgetting, the Multilingual Naming Test (MINT; Gollan, Weissberger, Runnqvist, Montoya, & Cera, 2012), a language history questionnaire (some questions drawn from Li, Zhang, Tsai, & Puls, 2014), and a release from PI task. Other cognitive tasks (e.g., color-shape switching, dot counting) were also completed, but since they are not relevant to the present research questions, the data from these tasks will not be included here. Each of the tasks listed above is outlined in further detail below. All participants completed the tasks in the same order. All stimuli were presented on a Dell Precision 3420 computer running Windows 7 Professional, and recordings of verbal responses were captured using a Marantz Professional PMD-561 handheld solid-state recorder. Stimuli for the letter fluency and MINT were presented via E-Prime 2.0, directed forgetting and release from PI stimuli were presented using Matlab 2016b, and all questionnaires and subsequent responses were presented and collected through Qualtrics online survey software.

Letter fluency. This task was included as a measure of language proficiency, as fluency tasks have commonly been used in previous studies to assess proficiency (e.g., Bice & Kroll, 2015; Beatty-Martinez & Dussias, 2017). Participants were seated in front of a computer and told that a letter of the alphabet would be presented on the screen, followed by an auditory tone, signaling the beginning of the recording. Once participants heard the tone, they were instructed to begin naming as many words as they could that began with the specific letter, excluding proper nouns (e.g., Nathan, Nantucket) and words with the same word stem but different suffixes (e.g., nest, nested, nesting). Participants were given 60 seconds for naming, and the letter remained on the screen throughout the duration of the trial. All participants completed one practice trial (the letter R) before beginning the experimental trials. If participants were monolingual, they completed four trials in English. If participants were bilingual, they completed two blocks consisting of four trials in English and four trials in Spanish. The blocks were counterbalanced such that half of the bilinguals in each age group received the English trials first, and half received the Spanish trials first. The letters D, N, A, and J were always presented together in the same block, and M, F, A, and J were always presented together, though the order of the letters was randomized for each participant. Half of the monolinguals saw the block with the letters D, N, A, and J, and half saw the block with the letters M, F, A, and J. Half of the bilinguals named words that began with the letters D, N, A, and J in English, and named words that began with M, F, A, and J in Spanish, and half the bilinguals performed the opposite.

Directed forgetting. In this item-method directed forgetting task (Sego et al., 2006; Titz & Verhaeghen, 2010), participants were shown a list of 46 words, presented one at a time. Each trial began with the presentation of a fixation cross for one second, followed by a word that appeared on the screen for three seconds. Participants were instructed to say the word out loud when it appeared on the screen. The word was then followed by a remember cue (“RRRR”) or a forget cue (“FFFF”) which was also presented on the screen for three seconds. Participants were instructed to remember the words that they were cued to remember, and likewise forget the words they were cued to forget. Forty out of the 46 words were critical study words that were divided into two lists of 20 words each. The task was counterbalanced such that half of each age group and each language group were cued to remember the List A words and forget the List B words, and half were cued to remember the List B words and forget the List A words. These 40 words were presented in a random order for each participant. The additional six words were always presented as the first three and last three words, and always appeared in the same order, with the same cue, to control for primacy and recency effects.

After participants studied all 46 words, they were given a brief distractor task in which they were given a blank map of the United States and asked to draw in as many of the state lines as they could and label their demarcations with the correct state names. They were given three minutes to work on this. After they finished, they were presented with a blank sheet of paper and asked to recall as many words as they possibly could. As is typical in a directed forgetting task, they were told that they could recall and write down both “remember” words and “forget” words, despite the instructions they were given at the beginning.

MINT. The MINT is a picture naming task that has been normed in English and Spanish. This task was used as the primary measure of vocabulary knowledge, in order to control for effects of vocabulary on resistance to PI memory performance as Bialystok and Feng (2009) did. In the MINT, pictures were presented on the screen, one at a time, and remained on the screen until the participant made a verbal response, at which time the experimenter manually pressed a button on the Chronos response box to move on to the next trial. If participants did not make a verbal response, the picture disappeared after five seconds. Participants were instructed to say the name of each picture, or if they did not know what the object was, they were instructed to say, "I don't know." The names of the pictures increase in vocabulary difficulty throughout the five practice trials and 68 experimental trials, and the total score on the experimental trials is used as a proxy of language proficiency. If participants were monolingual, they completed the MINT in English. If participants were bilingual, they completed the MINT in either Spanish or English during this testing session and completed the task in the other language during the second testing session.

Language history questionnaire (LHQ). All participants were given a questionnaire to assess various aspects of their language history and current language use. The LHQ was completed interview-style for all participants, to minimize confusion and inaccurate responses common with particular questions.

Release from PI. In this task, participants saw a series of 10 words, presented one at a time for three seconds each. The words were all semantically related, either belonging to the category of "body parts" or "occupations". They were instructed to say each word out loud as it appeared on the screen. After viewing the words, participants were instructed to count backwards by threes for 15 seconds, beginning with a three-digit number randomly generated by Matlab. Once 15 seconds was up, participants were given a sheet of paper and asked to recall as many words as they could from the list they had just seen. Once participants indicated that they recalled as many words as they could remember, they repeated the same sequence of tasks (encoding, backwards counting, and recall) three more times. Critically, the semantic category of the words was the same for the first three lists but changed for the fourth list. The lists were counterbalanced such that half of each age group and each language group saw body parts for the first three lists and occupations for the fourth list, and the other half saw occupations on the first three lists and body parts on the fourth list.

Session 2. During the second testing session, participants were consented, completed an MRI screening, and then underwent a 30-minute brain scan. Afterwards, participants completed a series of tasks including a flanker task, semantic fluency, and the MINT. Each of these tasks listed above is outlined in further detail below. All participants completed the tasks in the same order. All stimuli were presented on a Dell Latitude 5580 Laptop, and recordings of verbal responses were captured using a Yemenren R9 handheld voice recorder. Stimuli for all tasks were presented via E-Prime 2.0, and responses were made on a Chronos response box.

Flanker task. Participants were presented with screens that showed three rows of chevron arrows, with five arrows in each row. In two-thirds of experimental trials, all arrows were pointing in the same direction (congruent trials), and in one-third of experimental trials, the third arrow in the second row of arrows (the middle arrow in the middle row) was pointing in the opposite direction from the rest of the arrows (incongruent trials). Though a basic flanker task typically only consists of one row of arrows, the idea was that adding more perceptually distracting information around the target arrow might make inhibition of the irrelevant information more difficult when completing the task, thus engaging stronger conflict monitoring mechanisms in the bilinguals and more clearly distinguishing their performance from the monolinguals. Participants were instructed to indicate the direction of the middle arrow in each trial by pressing the left-most button on the response box for "left-pointing" and the right-most button on the response box for "right-pointing". Participants were given 12 practice trials before beginning the experimental trials. Experimental trials were divided into two blocks of 120 trials each. The number of congruent and incongruent trials in each block was the same (80 congruent trials, 40 incongruent trials).

Semantic fluency. Like letter fluency, this task was included as another measure of language proficiency. Participants were seated in front of a computer and told that a category name would be presented on the screen, followed by an auditory tone, signaling the beginning of the recording. Once participants heard the tone, they were instructed to begin naming as many words as they could think of that belonged to that particular category. Participants were given 60 seconds for naming, and the category remained on the screen throughout the duration of the trial. All participants completed one practice trial (colors) before beginning the experimental trials. If participants were monolingual, they completed four trials in English. If participants were bilingual, they completed two blocks consisting of four trials in English and four trials in Spanish. The categories were blocked such that clothing, drinks, sports, and vegetables always appeared together in the same block (though in a random order), and modes of transportation, furniture, fruits, and words associated with the beach were always presented in the same block, again in a random order for each participant. The blocks were counterbalanced such that half of the bilinguals in each age group received the English trials first, and half received the Spanish trials first. The monolinguals only received one of the two blocks of trials.

MINT (bilinguals only). If participants were bilingual, they completed whichever version of the MINT they did not complete during Session 1. For example, if the participant named the pictures in Spanish during the first session, they completed the MINT in English during the second session. The task was counterbalanced such that half of the bilinguals in each age group named the pictures first in English, then in Spanish, and half named the pictures first in Spanish, then in English across sessions.

Imaging parameters. Each participant was scanned on a 3T Siemens Prisma at the UC Riverside Center for Advanced Neuroimaging. The entire sequence took approximately 30 minutes. A whole-brain, T1-weighted magnetization prepared rapid gradient echo (MPRAGE) was acquired with repetition time (TR) = 2400 ms, echo time (TE) = 2.72 ms, field of view (FOV) = 256×256 mm, flip angle = 8°, 208 slices, and a spatial resolution of 0.8 mm^3.

Additionally, one diffusion-weighted echo-planar imaging (EPI) sequence was acquired in the anterior-to-posterior direction with TR = 3500ms, TE = 102 ms, FOV = 218×218 mm, 72 axial slices, and 1.7 mm^3 spatial resolution. For the sequence, gradients ($b = 1500$ and 3000 s/mm^2) were applied in 64 orthogonal directions, with six images having no diffusion weighting ($b = 0$). Immediately afterward, a second brief sequence with the same acquisition parameters was used to acquire six b0 volumes in the posterior to anterior direction, to use for field inhomogeneity correction during preprocessing.

MRI processing pipeline. All T1-weighted images were visually checked by a trained research assistant for artifacts such as missing brain, wrapping, ringing, ghosting, susceptibility, radiofrequency (RF) inhomogeneity and noise, and motion. FSLeyes was used for brain visualization. Any serious issues were confirmed by the study's primary investigator. Of note, the imaging data of two older adults were removed from the sample due to excessive motion and were not part of the set of 32 older adult brains used in the present analyses.

Anatomical measurements. Cortical reconstruction and volumetric segmentation for all participants was performed using the Freesurfer v 6.1 analysis suite (Dale, Fischl, & Sereno, 1999; Fischl, Sereno, & Dale, 1999; Fischl, Sereno, Tootell, & Dale, 1999), which is documented and freely available for download online (http://surfer.nmr.mgh.harvard.edu/). Briefly, processing includes motion correction and co-registration of T1-weighted images, removal of non-brain tissue, automated Talairach transformation, segmentation of deep grey and subcortical white matter volumetric structures, intensity normalization, tessellation of grey and white matter boundaries, automated topology correction, and surface deformation after intensity gradients optimally identify boundaries based on greatest intensity shifts. Manual inspection of the grey/white segmentation for all 164 hemispheres was performed. Once the cortical models were complete, the cerebral cortex was parcellated based on gyral and sulcal structure, and a variety of surface-based data including maps of cortical thickness representations were created using both intensity and continuity information from the entire three-dimensional MR volume. Procedures for the measurement of cortical thickness have been validated against histological analysis (Rosas et al., 2002) and manual measurements (Kuperberg et al., 2003; Salat et al., 2004). Cortical thickness, intracranial volume (ICV), and parcellation volume values were automatically extracted for each hemisphere by the Freesurfer software. During processing, surface images were produced and mapped onto an averaged surface for each hemisphere where the parcellations were performed using the Desikan parcellation atlas (Desikan et al., 2006). The individual surfaces were then nonlinearly warped back into individual subject space. Eleven regions of interest were chosen: bilateral ACC, IFG, and MFG, as well as the five parcellations of the corpus callosum (anterior, mid-anterior, central, mid-posterior, and posterior). Because the Desikan parcellation atlas subdivided the ROIs based on gyral and sulcal structure, a summing procedure was implemented in order to reconstruct them. Rostral and caudal ACC were combined to create an "ACC" ROI, pars opercularis, pars orbitalis, and pars triangularis were combined to create an "IFG" ROI, and rostral and caudal MFG were combined to create an "MFG" ROI, for each hemisphere. The volumes of the parcellations were summed together to determine a total grey matter volume for each combined ROI. For cortical thickness, in order to account for parcellations of varying sizes, the products of the parcellations' surface area and cortical thickness were summed together and divided by the sum of the surface area.[2]

I also conducted an exploratory analysis of the left and right hippocampi, since my tasks of interest were memory-based, and no studies have previously examined possible hippocampal differences between monolinguals and bilinguals. The left and

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[2] See the archived conversation from the Freesurfer listserv on this topic and the appropriate calculation at https://www/mail-archive.com/freesurfer@nmr.mgh.harvard.edu/msg16040.html.

right precentral and postcentral gyri (motor and somatosensory cortex, respectively) were included as control regions, since no structural differences would be expected as a function of bilingualism in these areas.

DTI processing pipeline. The diffusion-weighted data of all participants was processed with FSL's Diffusion Toolbox (FDT; Jenkinson et al., 2012). Brain tissue was extracted from non-brain tissue, and distortions induced by susceptibility and eddy currents were corrected for. A diffusion tensor model was computed at each voxel. To process the data for the TBSS analysis, the FA data was registered using FNIRT (FMRIB's Nonlinear Registration Tool). The target image used for the registrations was FSL's FMRIB58_FA standard space image, a high-resolution average of 58 FA images from participants aged 20-50. Next, all images were affine transformed into MNI152 space. A mean FA skeleton was created, which excluded non-white matter voxels by thresholding FA at 0.2, as well as an FA skeleton for each individual subject.

In order to create masks for my tracts of interest, I utilized the ICBM-DTI-81 White Matter Labels Atlas (Mori, Wakana, Nagae-Poetscher, & Van Zijl, 2005) as well as the JHU White Matter Tractography Atlas (Hua et al., 2008). Three separate masks were created for the corpus callosum (corresponding to the genu, body, and splenium), and masks were also created for bilateral cingulum, SLF, UF, and ILF. These regions were chosen based on my *a priori* and exploratory predictions mentioned previously.

Next, voxel-wise statistics on the skeletonized FA data were computed using the "randomize" command. Design matrices were created using FSL's GLM graphical user interface. Threshold-free cluster enhancement (TFCE) was used to correct for multiple comparisons and to visualize cluster-like structures without requiring a prior definition of a cluster-forming threshold. Skeletonized data for all participants was subjected to *F*-tests in order to test the main effect of age (younger v. older adult), the main effect of language group (bilingual v. monolingual), and the interaction between age and language group. I conducted whole-brain analyses for each dependent measure as well as group comparisons within each specific tract of interest. The relationships between whole-brain or tract-specific FA and behavioral measures, as well as the relationships between FA and grey matter indices, were also examined.

Chapter 3

Results

Sample Characteristics

Demographics. Refer to Table 2 for information (*M* and *SD*) regarding cognitive status, educational attainment, and laboratory-based proficiency measures for each of the four groups of participants. MoCA scores were comparable across all four groups ($M = 26.77$, $SD = 2.10$), with no significant differences between age groups, $F(1, 78) < 1$ or monolinguals versus bilinguals, $F(1, 78) = 2.53$, $p = .12$, indicating that all participants (particularly the older adults) were matched with regard to cognitive status. Education was quantified by asking participants to choose their highest level of education from a list of twelve possible options, ranging from "some elementary school" (coded as "1") to "Doctoral or advanced degree" (coded as "12"). On average, younger adults reported a mean education level of 7.2, where 7 is equivalent to "some college." Older adults reported average educational achievement of 8.9, where 9 is equivalent to "Associate's degree." Older adults in the sample were significantly more educated than the younger adults, $F(1, 78) = 22.62$, $p < .001$, but monolinguals and bilinguals did not differ with regard to education levels, $F(1, 78) < 1$, nor was there an interaction between age and language groups, $F(1, 78) = 3.15$, $p = .08$.

Table 2.
Means and (SDs) characterizing the cognitive status, educational attainment, and laboratory-assessed language proficiency by group.

	Younger Adults		**Older Adults**	
	Monolingual	Bilingual	Monolingual	Bilingual
MoCA	26.8 (1.9)	26.5 (1.7)	27.6 (2.5)	26.4 (2.4)
Education	7.0 (1.2)	7.4 (1.2)	9.3 (1.9)	8.4 (2.0)
MINT				
English	**62.0 (2.5)**	**59.0 (4.6)**	**64.0 (3.1)**	**60.2 (5.3)**
Spanish		43.3 (9.8)		45.3 (13.2)
Semantic Fluency				
English	**57.0 (10.4)**	**47.7 (11.2)**	**63.6 (9.6)**	**51.8 (11.5)**
Spanish		34.5 (10.6)		36.0 (9.4)
Letter Fluency				
English	**41.0 (11.2)**	**34.7 (10.4)**	45.6 (9.9)	39.3 (13.2)
Spanish		**28.6 (11.5)**		**37.5 (9.9)**

Note. **Bolded** scores indicate a significant difference ($p < .05$) between groups.

Task-based proficiency. Next, participants' MINT, semantic fluency, and letter fluency scores were compared. All participants completed the English version of each task, whereas only the bilinguals completed the Spanish version of the three tasks as well. The four groups were compared on English MINT performance using a 2 (age group) x 2 (language group) ANOVA. There was a main effect of language group such that the monolinguals performed significantly better than the bilinguals, $F(1, 78) = 14.69$, $p < .001$, but there were no differences between younger and older adults, $F(1, 78) = 3.17$, $p = .08$, nor was there an interaction effect, $F(1, 78) < 1$. The monolingual English speakers had higher English vocabulary compared to the Spanish-English bilinguals, which is not surprising considering the robust literature that has found bilinguals generally have smaller vocabularies in each language compared to the vocabulary of a monolingual (e.g., Bialystok & Luk, 2012). When considering the bilinguals' performance on the Spanish MINT, there was no difference between the younger and older adults, $t(39) = .54$, $p = .59$, hence bilinguals were comparable in their Spanish vocabulary knowledge. Still, the bilinguals knew significantly fewer words in Spanish compared to English, $t(40) = 7.92$, $p < .001$.

As mentioned previously, semantic and letter fluency are commonly used as task-based measures of proficiency and vocabulary knowledge in each language. Participants' English semantic fluency scores were compared using a 2x2 ANOVA and a main effect of age was found, with older adults producing more exemplars than younger adults, $F(1, 78) = 4.90$, $p = .03$. In general, this age effect for fluency tasks is typical, given that older adults tend to have larger vocabularies than younger adults (Bialystok & Luk, 2012). Additionally, there was a main effect of language group, with monolinguals producing more English exemplars than bilinguals, $F(1, 78) = 18.92$, $p < .001$. No interaction effect was present, $F(1, 78) < 1$. I also utilized a 2x2 factorial ANOVA to compare English letter fluency scores and did not find a significant difference between younger and older adults, though the older adults recalled a greater number of exemplars on this task as well, *F*(1, 78) = 3.21, *p* = .08. As with English semantic fluency, there was a main effect of language group, with monolinguals producing more English exemplars than the bilinguals, *F*(1, 78) = 6.25, *p* = .01, but no interaction, *F*(1, 78) < 1.

When comparing the bilingual younger and older adults on their Spanish semantic and letter fluency scores, a significant age difference was evident for letter fluency, *t*(39) = 2.56, *p* = .01, but not for semantic fluency, *t*(39) = 0.46, *p* = .65. In the case of Spanish letter fluency, older bilinguals generated significantly more exemplars than the young adult bilinguals. Past research on participants ranging in age from children to older adults (Friesen, Luo, Luk, & Bialystok, 2015) has found that letter fluency requires more executive control than semantic fluency, so fewer exemplars are typically produced on the letter fluency task. However, this was not the case for the sample of bilingual older adults – on average, their Spanish semantic and letter fluency scores were not significantly different (see Table 2). This pattern of findings highlights the possibility that the older bilinguals have better executive control abilities as a function of knowing two languages for many more decades when compared to the younger adult bilinguals, which is addressed further in the following section.

Bivariate correlation analyses were also conducted between all participants' English MINT, English semantic fluency, and English letter fluency scores to test the convergent validity of the tasks. All three constructs were significantly related, with English semantic and letter fluency scores correlating the most strongly, *r*(80) = .62, *p* < .001. English MINT scores were also correlated English semantic fluency, *r*(80) = .60, *p* < .001, and English letter fluency, *r*(80) = .49, *p* < .001. Scatterplots were inspected and were determined to have appropriate range and variability.

Similarly, the Spanish MINT, semantic fluency, and letter fluency scores of the bilinguals were correlated, and as with the English versions of the tasks, all three measures were significantly related. Spanish letter and semantic fluency exhibited the strongest correlation, *r*(39) = .65, *p* < .001, followed by the MINT and semantic fluency, *r*(39) = .60, *p* < .001, and the MINT and letter fluency, *r*(39) = .58, *p* < .001. As with the prior data, the scatterplots of the relationships between these three tasks were inspected and determined to have appropriate range and variability.

Self-reported proficiency. As part of the language history questionnaire, participants were asked to self-report their current proficiency in English (if they were monolingual) or in English and Spanish (if they were bilingual), as well as the age at which they learned each language (AoA). Refer to Table 3 for the means and standard deviations of each group with regard to their self-reported proficiency scores. Proficiency ratings in each language were further broken down into four sub-categories: speaking, reading, writing, and understanding, which each participant rated on a scale from 0-10 (0 = “None”, 10 = “Native-like”).

Table 3.

Means and (SDs) characterizing the self-reported language proficiency for each group.

	Younger Adults		**Older Adults**	
	Monolingual	Bilingual	Monolingual	Bilingual
English Proficiency				
Speaking	9.6 (0.9)	9.4 (0.9)	**9.7 (0.6)**	**8.9 (1.2)**
Reading	9.5 (0.9)	9.4 (0.9)	**9.7 (0.6)**	**8.9 (1.2)**
Writing	9.2 (1.3)	9.3 (1.0)	**9.6 (0.7)**	**8.9 (1.2)**
Understanding	9.6 (0.8)	9.6 (0.8)	9.6 (0.7)	9.1 (1.1)
English AoA	**0.5 (1.0)**	**3.3 (2.3)**	**0.5 (1.0)**	**4.4 (5.8)**
English Use - At Home		**37.4 (26.2)**		**78.4 (21.5)**
English Use - Free Time		70.7 (21.7)		80.0 (18.8)
Spanish Proficiency				
Speaking		8.3 (1.7)		8.2 (2.1)
Reading		8.1 (1.6)		7.4 (2.4)
Writing		7.0 (2.0)		6.7 (2.7)
Understanding		**9.1 (1.4)**		**8.0 (2.0)**
Spanish AoA		0.6 (1.1)		1.8 (3.7)
Spanish Use - At Home		**63.6 (25.1)**		**21.6 (21.5)**
Spanish Use - Free Time		28.5 (22.4)		20.0 (18.8)

Note. **Bolded** scores indicate a significant difference ($p < .05$) between groups.

On average, all four groups were highly proficient in English, with older bilinguals self-reporting the lowest overall proficiency (*M* = 8.95, *SD* = 1.16) and older monolinguals reporting the highest proficiency (*M* = 9.65, *SD* = 0.65). A 2x2 MANOVA was used for group comparisons, with the independent factors of age and language group, and the dependent variables of English speaking, reading, writing, and understanding. The only significant effect was a language group difference on English speaking ability, such that monolinguals (*M* = 9.63, *SD* = 0.80) reported greater proficiency than bilinguals (*M* = 9.24, *SD* = 1.02), *F*(1, 78) = 4.88, *p* = .03. When comparing within age groups, younger bilinguals and monolinguals did not differ in any aspect of their English proficiency, *t*(48) < 1, whereas older monolinguals reported significantly higher proficiency than older bilinguals in speaking, *t*(30) = 2.26, *p* = .03, reading, *t*(30) = 2.26, *p* = .03, and writing, *t*(30) = 2.14, *p* = .04, but not understanding, *t*(30) = 1.69, *p* = .10 (see Table 3). As expected, there was a significant difference between bilingual and monolingual AoA, *F*(1, 78) = 25.65, *p* < .001, such that monolinguals acquired English from birth (*M* = 0.49, *SD* = 0.98), whereas the bilinguals acquired English around age four (*M* = 3.71, *SD* = 3.98). There was no statistical difference between when the older and younger bilinguals acquired English, *t*(39) < 1. Because the entire sample was highly proficient in English, overall proficiency correlated weakly, yet significantly, with AoA, *r*(80) = -.27, *p* = .01.

With regard to Spanish proficiency, the younger and older adult bilinguals only differed on the variable of Spanish understanding, with younger adults reporting greater comprehension of Spanish, *t*(39) = 2.10, *p* = .04 (see Table 3). There was also no statistical difference between the age at which the older and younger bilinguals acquired Spanish, $t(39) = 1.60$, $p = .12$. Because the bilinguals were highly proficient in Spanish on average, there was only a weak, non-significant correlation between Spanish AoA and overall Spanish proficiency, $r(39) = -.28$, $p = .07$.

Task-based and self-reported proficiency correlations. Finally, I was interested in how well one's self-reported proficiency in English or Spanish related to their performance on the task-based proficiency measures. After conducting bivariate correlation analyses, it was evident that overall self-rated English proficiency (a composite of English speaking, reading, writing, and understanding) for all participants was positively related to performance on each of the three proficiency tasks, including English MINT, $r(80) = .33$, $p = .002$, English semantic fluency, $r(80) = .32$, $p = .004$, and English letter fluency, $r(80) = .36$, $p < .001$. Similarly, among the bilinguals, overall Spanish self-rated proficiency (again, a composite of Spanish speaking, reading, writing, and understanding) was positively related to performance on the Spanish MINT, $r(39) = .70$, $p < .001$, Spanish semantic fluency, $r(39) = .46$, $p = .002$, and Spanish letter fluency, $r(39) = .41$, $p = .007$. These relationships were all significant even after applying a false discovery rate (FDR) correction of $p < .05$.

For the bilinguals, I also examined how the age at which one acquired their languages, as well as how the frequency of use of each of their languages, related to task-based measures of proficiency. English AoA was positively associated with Spanish MINT scores, $r(39) = .52$, $p = .004$, Spanish semantic fluency, $r(39) = .33$, $p = .04$, and Spanish letter fluency, $r(39) = .34$, $p = .03$, suggesting that the later in life the bilingual participants learned English, the better they performed on the Spanish task-based measures of proficiency. Additionally, the more that the bilinguals used Spanish in their free time, the lower their score was on the English version of the MINT, $r(39) = -.31$, $p = .05$. Taken together, these findings suggest task-based and self-report measures are tapping into the same constructs measuring language proficiency.

Summary of sample characteristics. Overall, these results are typical of what has been reported in the literature previously: bilinguals tend to have smaller vocabularies in each of their languages compared to English monolinguals, which held true across all three of the tasks participants were given to measure their English vocabulary knowledge and fluency. All of the participants were highly proficient in English, and the majority of the bilinguals self-reported high Spanish proficiency as well. However, the bilinguals' performance on the MINT, semantic fluency, and letter fluency tasks suggest that as a whole, they were more proficient in English compared to Spanish, as evidenced by higher scores on the English portion of each task. This is likely a byproduct of living in an English-immersive environment; both the younger and older adults reported using Spanish in their free time less than 30% of the time.

Interestingly, the younger adult bilinguals used Spanish significantly more at home compared to the older adults – nearly 64% of the time. As is typical for heritage bilinguals, many of the young adult participants reported that their primary caretakers spoke to them exclusively in Spanish growing up, and it is possible that these caretakers remain more comfortable communicating in Spanish to their children (the participants) compared to English. However, it is unclear why the older bilinguals are using English to a much greater degree in the home. Given that the older and younger bilinguals are all highly proficient (see Table 3), it is unlikely that differences in Spanish abilities are playing a role. One possibility is that these participants are an older version of the young adult heritage speakers from this sample – nearly two-thirds (62.5%) of the older bilinguals reported that Spanish was the first language they learned, and these individuals spoke Spanish in the home as children anywhere from 50-100% of the time. However, these older bilinguals have also spent a lifetime immersed in an English-dominant society; speaking English every day to colleagues at work or in other social settings might have influenced the amount of English that they spoke in the home over time, as well. Either way, this difference between the two groups of bilinguals is an obvious cohort effect that will be addressed further in the discussion section.

Another point of interest is that although bilingual younger and older adults self-reported similar English and Spanish proficiency, with the older bilinguals generally rating themselves lower in both languages compared to the young adults (though not significantly so, apart from Spanish understanding ratings), the older bilinguals tended to perform better on the MINT, semantic fluency, and letter fluency in both languages compared to the bilingual young adults. This pattern of findings suggests one of three possibilities: the bilingual older adults were more conservative in their self-reported proficiency ratings, the bilingual young adults were overconfident in their ratings, or a combination of the two. It is possible that since the young adult bilinguals use Spanish more often, their perception of how proficient they are in Spanish is skewed to reflect greater proficiency; on the other hand, since the older bilinguals use Spanish less in their day-to-day lives, they might have less confidence in their Spanish abilities. Either way, it is clear that the bilinguals are highly proficient in both languages, and whether differences in proficiency between the bilinguals and monolinguals have any effect on behavioral task performance will be examined further in the following section.

Behavioral Findings

Directed forgetting. A 2x2 factorial MANCOVA was conducted with two between-subjects variables, age group (younger v. older adult) and language group (monolingual v. bilingual) and two dependent variables (proportion of to-be-remembered words retrieved, and proportion of to-be-forgotten words retrieved). English MINT score was included as a covariate to control for differences in vocabulary.

For to-be-remembered (TBR) words, there was a main effect of age group, such that younger adults retrieved more TBR words than the older adults (see Figure 1A), $F(1, 77) = 6.92$, $p = .01$, but no significant differences between bilinguals and monolinguals, $F(1, 77) < 1$, and no interaction between age and language group, $F(1, 77) < 1$. Vocabulary was also not a significant covariate, $F(1, 77) = 1.93$, $p = .17$. For to-be-forgotten (TBF) words, there were no main effects of age group, $F(1, 77) < 1$, or language group, $F(1, 77) = 1.24$, $p = .27$, and no interaction effect, $F(1, 77) < 1$ (see Figure 1B). Vocabulary was not a significant covariate, $F(1, 77) = 2.00$, $p = .16$.

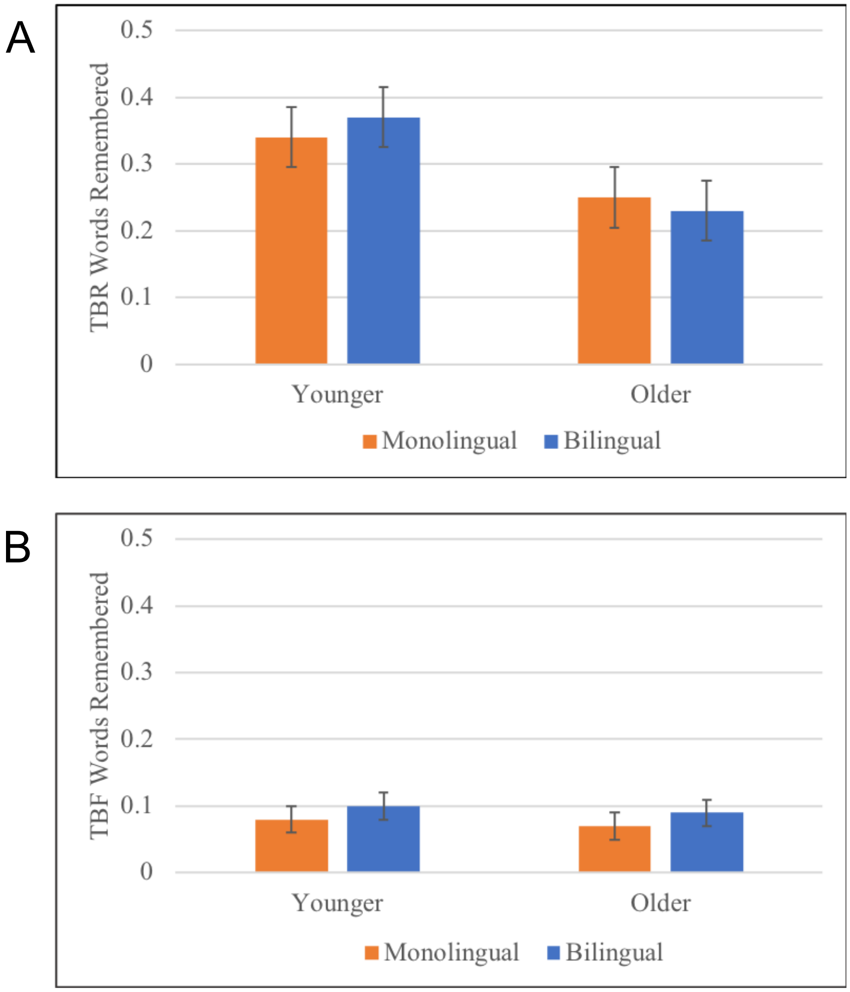

Figure 1. Younger adults retrieved significantly more to-be-remembered (TBR) words than older adults (A), but not more to-be forgotten (TBF) words (B), in the directed forgetting task.

Release from PI. A 2x2x4 factorial MANCOVA was conducted with two between-subjects variables, age group (younger v. older adult) and language group (monolingual v. bilingual), the within-subjects variable of list, and two dependent variables (proportion of words correctly recalled per list, and proportion of intrusions per list; intrusions occur when words from one list are incorrectly retrieved during recall of another list). English MINT score was again included as a covariate.

Older and younger adults did not differ in their proportion of correct recall, *F*(1, 311) = 2.12, *p* = .15, nor were there significant differences between monolinguals and bilinguals, *F*(1, 311) < 1. There was a list effect, *F*(3, 311) = 14.68, *p* < .001 (see Figure 2). Post-hoc analyses using paired *t*-tests indicated that participants as a whole recalled more words correctly on List 1 compared to List 2, *t*(81) = 4.26, *p* < .001, and List 3, *t*(81) = 4.60, *p* < .001. However, participants typically showed the best recall performance on List 4, with performance being significantly greater on this list than Lists 1, 2, and 3 (*p* ≤ .01 for all comparisons). Recall on Lists 2 and 3 did not differ significantly from one another, *t*(81) = .60, *p* = .55. There were no interaction effects, nor was vocabulary a significant covariate, *F*(1, 311) < 1.

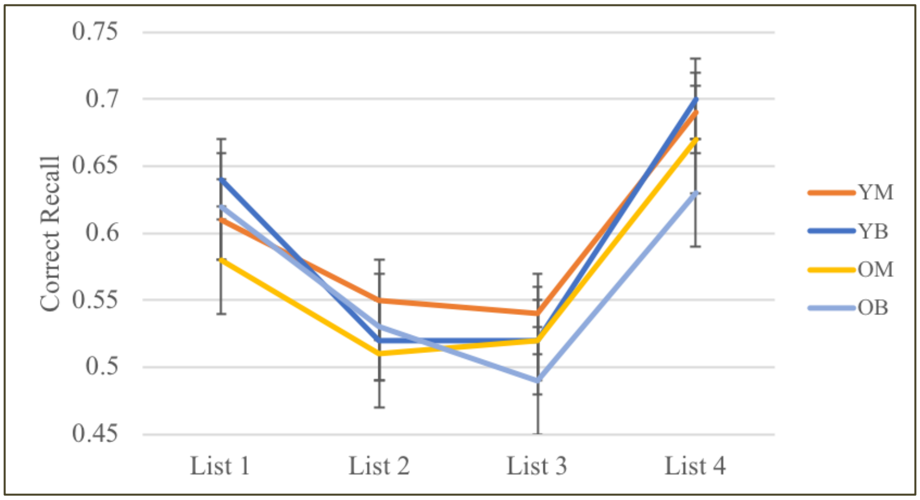

Figure 2. Proportion of words from each list correctly recalled by group. For all groups, buildup of interference between Lists 1 and 3 is followed by a release from PI on List 4.

Younger adults had significantly fewer intrusions than older adults, $F(1, 311) = 15.40$, $p < .001$, demonstrating an age group effect. Again, there was a main effect of list, $F(3, 311) = 9.98$, $p < .001$. Follow-up analyses comparing number of intrusions across the lists found that participants committed significantly fewer intrusion errors on List 1 compared to List 2, $t(81) = -2.86$, $p = .005$, and List 3, $t(81) = -4.18$, $p < .001$. Participants also had a lower proportion of intrusions on List 4 in comparison to List 2, $t(81) = 2.78$, $p = .007$, and List 3, $t(81) = 4.83$, $p < .001$, which supports the typical release from PI effect. There was also a significant difference between Lists 2 and 3, such that participants committed significantly more intrusion errors on List 3, $t(81) = -2.01$, $p = .05$, which is consistent with typical patterns of buildup of interference across lists.

There was also an age by list interaction, $F(3, 311) = 2.92$, $p = .03$. When the sample was split by age group, only the older adults showed greater interference (defined as more intrusion errors) on List 2, $t(81) = -3.39$, $p = .002$, and List 3, $t(81) = -4.65$, $p < .001$, compared to List 1 (seen in Figure 3). Older adults also made significantly fewer intrusion errors on List 4 compared to List 2, $t(81) = 2.46$, $p = .02$, and List 3, $t(81) = 4.14$, $p < .001$. Together, these results confirm the pattern of PI buildup and release. The younger adults did not experience a significant buildup of intrusions across Lists 1-3. However, there was a significant difference between List 3 and List 4, $t(81) = 2.84$, $p = .007$, suggesting the younger adults also experienced release from interference. There were no significant differences between the bilingual and monolingual groups with regard to intrusion errors, $F(1, 311) = 1.68$, $p = .20$, nor were there any other interaction effects, $F(1, 311) < 1$. Vocabulary was not a significant covariate, $F(1, 311) < 1$.

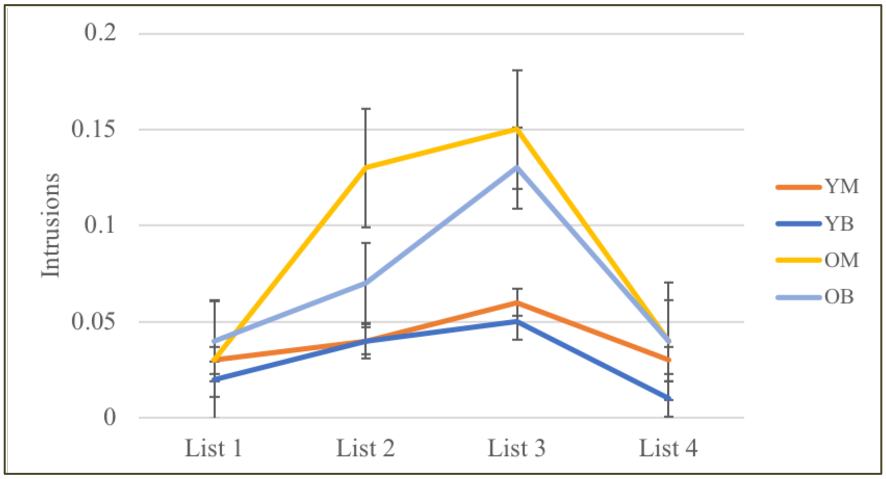

Figure 3. Proportion of intrusions incorrectly recalled by each group. Only older adults showed significantly more interference on Lists 2 and 3 compared to Lists 1 and 4.

Correlation of memory tasks. Because both the directed forgetting and release from PI tasks were chosen for the present study due to the belief that these tasks would tap into the construct of resistance to PI, bivariate correlation analyses were performed between the tasks' dependent measures. For the directed forgetting task, performance was quantified in two ways: the proportion of to-be-remembered (TBR) words retrieved (higher proportion equals better performance), and the proportion of to-be-forgotten (TBF) words retrieved (lower proportion equals better performance). Four performance variables were considered from the release from PI task: *buildup of interference*, defined as the difference between List 3 accuracy and List 1 accuracy, *release from interference*, or the difference between List 3 and List 4 accuracy, *buildup of intrusions*, or the difference between List 3 and List 1 intrusions, and *release from intrusions*, defined as the difference between the number of List 3 and 4 intrusions.

When correlating the two directed forgetting measures with the four release from PI measures across the entire sample, none of the relationships were significant, *p* > .50 for all. However, when the sample was divided by language group, two significant relationships emerged for the bilinguals only: a greater proportion of TBR words correctly retrieved was associated with less buildup of intrusions, *r*(39) = -.48, *p* = .001, and with less release from intrusions, *r*(39) = -.34, *p* = .03. Scatterplots of these relationships can be found in Figure 4. It is important to note that once the bilinguals were further separated by age group, only the significant relationship between TBR recall and buildup of intrusions remained for the young adults, *r*(23) = -.48, *p* = .02, suggesting that these relationships between task outcomes are not as strong among older bilinguals. Nevertheless, it appears that in general, the better that bilinguals did at accurately retrieving the TBR words on the directed forgetting task, the less interference (quantified as intrusions here) they experienced in the release from PI task.

Resistance to PI and MoCA scores. I was interested in whether MoCA performance was related to memory performance on the two resistance to PI tasks, since a large proportion of the MoCA taps into memory abilities. In order to investigate this further, I conducted a 2x2x2 factorial ANOVA with the independent variables of age (younger v. older adult), language group (monolingual v. bilingual) and MoCA performance (high v. low performer). A median split was calculated on the MoCA data across the whole sample to determine high versus low performers; high performers were characterized as participants who achieved a MoCA score between 27-30, and low performers achieved a score between 22-26.

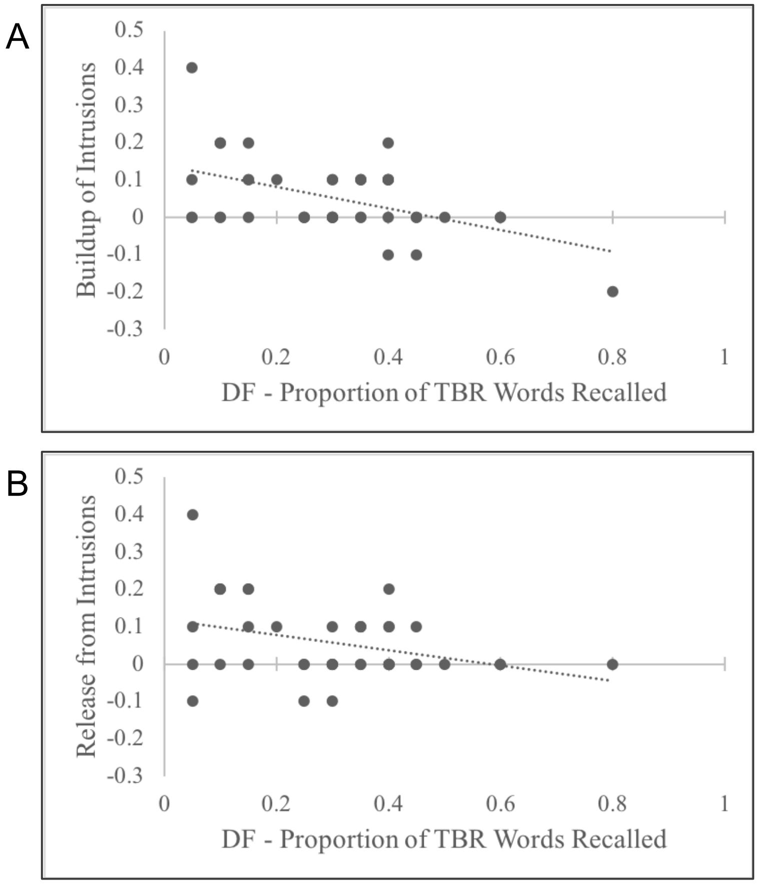

Figure 4. A negative relationship between directed forgetting and release from PI task performance among bilinguals. Remembering more TBR words in the directed forgetting task was related to A) less buildup of intrusions across Lists 1-3 and B) less release from intrusions between Lists 3 and 4 on the release from PI task.

There was a significant main effect of MoCA score, such that high MoCA performers recalled more TBR words than low MoCA performers, $F(1,74) = 8.04$, $p = .006$. There was also a language group by MoCA score interaction, $F(1, 74) = 10.212$, $p = .002$ (see Figure 5). Bilinguals did not differ in their directed forgetting TBR recall performance by whether they scored highly or not on the MoCA, $t(39) < 1$, but monolinguals did – monolinguals that were low MoCA performers remembered significantly fewer TBR words than high MoCA-scoring monolinguals, *t*(39) = -4.14, *p* < .001. There were no significant differences between groups on any other dependent measures, including TBF recall and the release from PI outcome variables, *p* > .05 for all comparisons. As might be expected, these findings suggest that neuropsychological test performance is predictive of declarative memory performance, but interestingly, this is only accurate for the participants that only know one language. These findings might imply that the low MoCA bilinguals are exhibiting some sort of protective effect on memory as a function of knowing multiple languages.

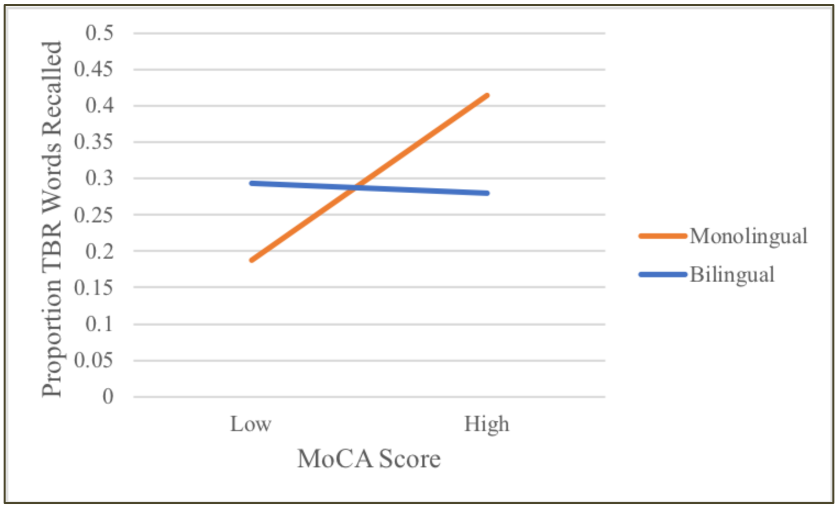

Figure 5. A significant interaction with regard to directed forgetting performance (specifically, TBR word recall) between low versus high MoCA performers by language group status.

Bilingual experience and memory correlations. I hypothesized that variables characterizing the bilingual experience, such as AoA, proficiency, and frequency of use of Spanish and English, should each relate to memory performance in bilinguals of both age groups. I conducted bivariate correlational analyses between these measures across the entire bilingual sample but did not find any significant results, $p > .05$ for all correlations. However, breaking the sample down by age group revealed some interesting relationships that were only present for the older adult bilinguals. For example, release from interference was significantly negatively correlated with Spanish understanding, $r(14) = -.57$, $p = .02$ (see Figure 6A), and with the proportion of time that the older bilinguals use Spanish in their free time, $r(14) = -.61$, $p = .01$ (see Figure 6B). This indicates that those who use Spanish more and better understand Spanish had a smaller improvement in correct recall from List 3 to List 4. However, when a median split was performed on the data, the older bilinguals with high Spanish understanding (those who self-reported their understanding as a 9 or 10 out of 10) recalled significantly more words correctly on List 3 of the release from PI task compared to older adults with moderate Spanish understanding (self-reported understanding between 5-8), $t(14) = 2.30$, $p = .04$ (see Figure 6C). Taken together, these findings seem to suggest that those who comprehend Spanish better obtain less release from interference due to the fact that they have better List 3 recall to begin with. In other words, the improvement from List 3 to List 4 will be larger for someone who experiences more PI across the first three lists, but if one experiences less PI, then recall is fairly stable across all lists and will not fluctuate as dramatically between List 3 and 4. Therefore, there may be some kind of benefit to memory as a function of being a proficient bilingual in old age.

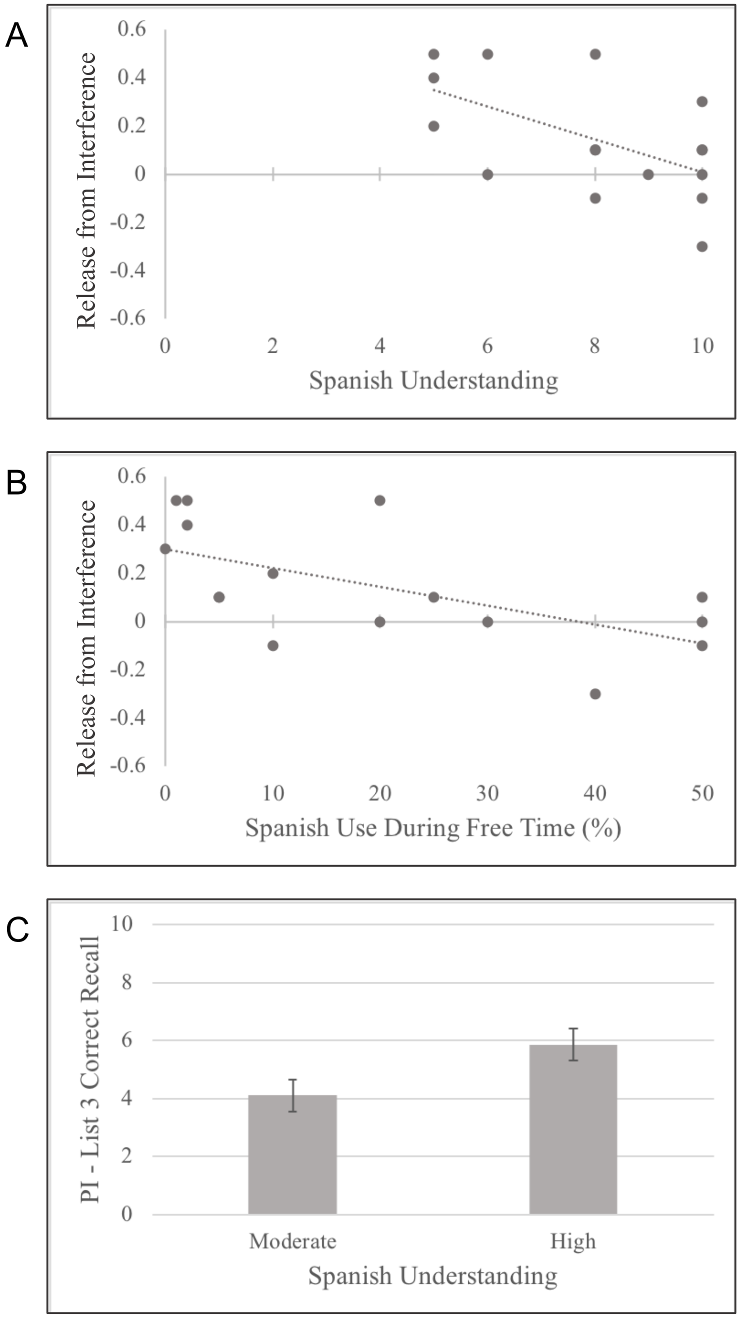

Figure 6. Older adult bilingual performance on the release from PI task is related to Spanish understanding and frequency of Spanish use. A) Older bilinguals with greater Spanish understanding demonstrate less release from interference. B) Older bilinguals who use Spanish more frequently during free time demonstrate less release from interference. C) Older adults who are "high" in Spanish understanding recall more words on List 3 compared to bilinguals who are "moderate" in Spanish understanding.

Among the younger bilinguals, greater Spanish understanding correlated negatively with buildup of interference, *r*(23) = -.42, *p* = .04 (see Figure 7A), and release from intrusions, *r*(23) = -.46, *p* = .02 (see Figure 7B). Thus, better performance on the release from PI task (quantified as more accurate recall and fewer intrusions on List 3) was associated with better Spanish understanding. None of the other bilingual experience variables and dependent measures of memory performance were meaningfully or significantly correlated with one another.

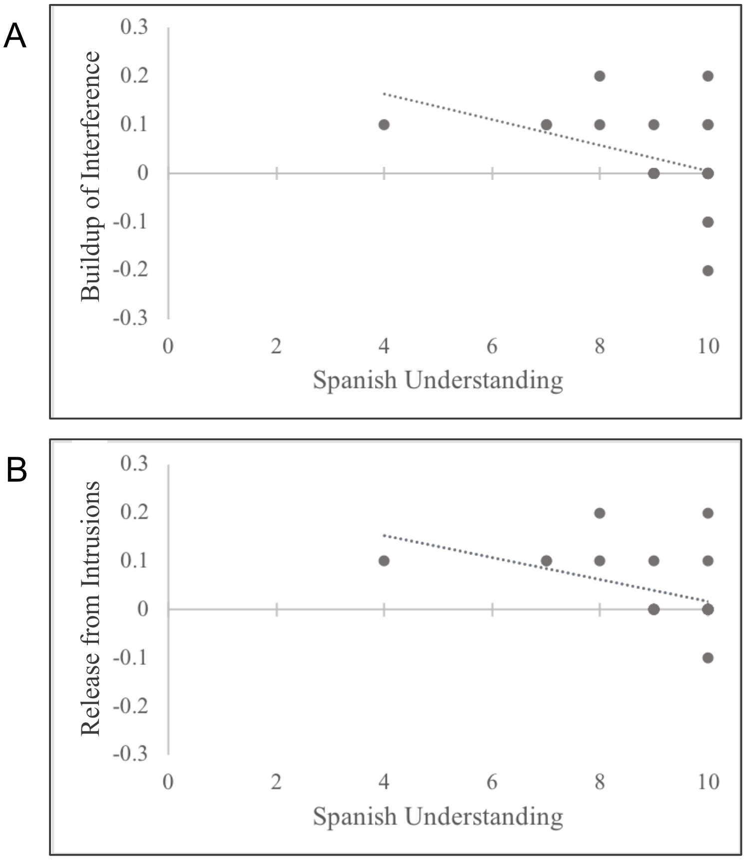

Figure 7. Spanish understanding among the young adult bilingual sample is negatively correlated with A) buildup of interference and B) release from intrusions, suggesting individuals who are more fluent in Spanish suffer from less proactive interference on the release from PI task.

Flanker task. I was interested in examining flanker task performance among the four groups, as it provides performance data for a complementary yet distinct measure of inhibition: resistance to distractor interference. Group comparisons were carried out using a 2 (age group) × 2 (language group) MANOVA, with accuracy (operationalized as proportion correct) and response time (ms) for congruent and incongruent trials serving as the dependent measures. Means for each group can be found in Table 4. Due to corrupted files, flanker task data for four participants (one older monolingual, two older bilinguals, and one younger bilingual) could not be recovered; therefore, the sample size was reduced to 78 participants for the following analyses.

There was a significant age effect for accuracy on incongruent trials, $F(1, 74) = 9.90$, $p = .002$, such that the older adults were more accurate. However, this finding should be interpreted with caution due to the ceiling effect present for all groups with regard to task accuracy. As such, there was no age effect for accuracy on congruent trials, or language group differences on congruent or incongruent trials, $F(1, 74) < 1$.

Table 4.

Mean accuracy (proportion correct) and response time (ms) for congruent and incongruent trials in the flanker task, by age and language group.

Accuracy

	Congruent	Incongruent
Younger Adults		
Monolingual	0.98 (0.004)	0.93 (0.01)
Bilingual	0.99 (0.004)	0.95 (0.01)
Older Adults		
Monolingual	0.99 (0.005)	0.98 (0.01)
Bilingual	0.99 (0.005)	0.98 (0.01)

Response Time

	Congruent	Incongruent
Younger Adults		
Monolingual	446.06 (35.81)	510.71 (69.86)
Bilingual	496.46 (35.09)	641.32 (68.45)
Older Adults		
Monolingual	623.62 (45.29)	747.95 (88.36)
Bilingual	806.64 (46.88)	1004.81 (91.46)

Note. Standard errors are listed in parentheses next to each mean value.

Significant main effects of age were present for both congruent and incongruent trial response times, $F(1, 74) = 35.18$, $p < .001$, and $F(1, 74) = 14.02$, $p < .001$, respectively. Younger adults were faster on both trial types. Additionally, the analyses revealed that the bilinguals were slower than monolinguals on both congruent trials, $F(1, 74) = 8.06$, $p = .006$, and incongruent trials, $F(1, 74) = 5.83$, $p = .02$. No interaction effects were present for either trial type, $p > .10$ for both congruent and incongruent trials.

A 2x2 between-subjects ANOVA was also computed to test group differences in the flanker interference effect, which for each participant was quantified as the difference between their average incongruent and congruent response times divided by the sum of their average incongruent and congruent response times. The analysis revealed no main effects of age, $F(1, 74) < 1$, language group, $F(1, 74) = 1.12$, $p = .30$, or any interactions, $F(1, 74) < 1$.

I also examined whether participants' flanker task performance correlated with their memory performance, since both tasks measure inhibitory abilities. However, no significant relationships were found between the flanker effect and any of the directed forgetting or release from PI dependent measures, $p > .05$ for all correlations tested.

Summary of behavioral findings. Overall, older adults performed more poorly on the two resistance to PI measures, remembering fewer TBR words in the directed forgetting task and experiencing more intrusions in the release from PI task. There were no group differences between monolinguals and bilinguals, suggesting that overall performance between the language groups is comparable. However, certain aspects of performance on the two tasks were significantly associated for the bilinguals only; for example, the number of TBR words recalled was negatively related to both buildup and release from intrusions. This pattern of findings implies that a different set of cognitive abilities are being recruited for these two tasks for the bilinguals compared to the monolinguals. This explanation would also help explain the interaction between MoCA scores and directed forgetting (TBR recall) performance - the cognitive abilities that the bilinguals are using for directed forgetting appear to be independent of cognitive status, while for the monolinguals they are more tightly linked.

Not only was performance on the two tasks related for the bilinguals, but certain aspects of the bilingual experience also related to resistance to PI abilities, specifically performance on the release from PI task. Spanish understanding was an important predictor of release from PI performance among both the younger and older adult bilinguals, implying that the better one is at Spanish, the better one is at resisting interference. These findings suggest that something about knowing and comprehending a second language is yoked to resistance to PI performance.

Finally, it appears that a different type of inhibition is being utilized for the flanker task in comparison to the resistance from PI tasks, evidenced by the fact that there was no relationship between performance on these tasks. This supports Friedman and Miyake's (2004) suggestion that resistance to distractor interference (e.g., flanker task) and resistance to PI are distinct and unrelated types of inhibition. However, it is also important to note here that the lack of relationship between the directed forgetting and release from PI tasks appears to go against Friedman and Miyake's other suggestion that resistance to PI is a unique and unitary construct. As with the resistance to PI tasks, older adults performed more poorly (slower) on both trial types in the flanker task compared to the young adults, and interestingly, bilinguals were slower overall compared to monolinguals. This is contradictory to findings that typically suggest bilinguals are faster to respond on such tasks, as a function of the ability to filter out perceptual distractors more quickly (Abutalebi et al., 2012). The reasons for this and the other aforementioned findings will be further explored in the discussion section.

Brain Structure Findings

Grey matter volume. Group comparisons of whole-brain (both cortical and total GMV) and ROI GMV were conducted using a 2 (age group) × 2 (language group) MANCOVA. Estimated total intracranial volume (eTIV) was included as a covariate in all analyses to correct for differences in head size between individuals. In order to account for multiple comparisons in the ROI analyses, a false discovery rate (FDR) corrected significance cutoff of $p < .05$ was used.

As expected, eTIV was a significant covariate for all predictors, $p < .001$, and there was a significant main effect of age for all eight comparisons, such that younger adults had greater GMV in each ROI (see Table 5 for means) as well as across cortical grey matter ($M_{young} = 496{,}086$ mm^3, $M_{old} = 435{,}763$ mm^3) and whole-brain grey matter ($M_{young} = 668{,}829$ mm^3, $M_{old} = 589{,}597$ mm^3) compared to the older adults, $p < .001$. However, there were no main effects of language group, suggesting that monolinguals did not differ significantly from bilinguals in either whole-brain or ROI volume comparisons, $p > .20$ for all tests. While in general monolingual younger adults showed greater GMV in the ROIs compared to younger bilinguals, and monolingual older adults showed less GMV in the ROIs compared to older bilinguals (see Table 5), with the conservative significance cutoff there were no significant interactions.[3]

Table 5.
Mean grey matter volume (mm^3) for each group within each of the six cortical regions of interest – bilateral ACC, IFG, and MFG.

	Younger Adults		**Older Adults**	
	Monolingual	Bilingual	Monolingual	Bilingual
Left ACC	4902 (142)	4372 (142)	3876 (177)	4025 (177)
Right ACC	4775 (127)	4434 (127)	3677 (158)	3934 (159)
Left IFG	12227 (202)	11971 (201)	9702 (252)	10146 (252)
Right IFG	12275 (168)	11886 (168)	9758 (210)	9677 (210)
Left MFG	24234 (476)	23145 (475)	19580 (594)	20061 (595)
Right MFG	24368 (442)	22831 (441)	19624 (552)	20123 (553)

Note. Means are adjusted due to the presence of the covariate eTIV. Numbers in parentheses are standard errors.

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[3] When using an uncorrected significance threshold of $p < .05$, significant interactions were present in left ACC, $F(1, 77) = 4.49$, $p = .04$, right ACC, $F(1, 77) = 4.36$, $p = .04$, and right MFG, $F(1, 77) = 4.15$, $p = .05$. In all three cases, there was a crossover interaction such that monolingual young adults displayed greater GMV than the bilingual young adults, but among the older adults, bilinguals displayed greater GMV than the monolinguals.

Follow-up comparisons within age group showed significant differences between the younger monolinguals and bilinguals for left ACC only, $t(48) = 2.46$, $p = .02$, and no significant differences between the older monolinguals and bilinguals for any of the three ROIs. When comparing within language group, there were significant differences between younger and older bilinguals for all three ROIs, $p < .05$ for all comparisons, as well as significant differences between younger and older monolinguals for all three ROIS, $p < .001$ for all comparisons. This pattern of findings suggests that monolinguals may experience steeper rates of decline in regions important for resistance to PI as they age, compared to bilinguals.

Cortical thickness. Group comparisons of whole-brain and ROI cortical thickness were conducted using a 2×2 MANOVA. Cortical thickness measures are largely independent of head size (https://surfer.nmr.mgh.harvard.edu/fswiki/eTIV), so eTIV was not included as a covariate. As before, an FDR-corrected significance cutoff of $p < .05$ was adopted for the ROI analysis, to account for multiple comparisons.

All seven tests resulted in a significant age effect, $p < .001$, with younger adults having thicker cortex in each of the six ROIs, as well as on average across the entire cortical surface. In addition, there was a significant main effect of language group for whole-brain cortical thickness, $F(1, 78) = 12.81$, $p = .001$, such that the monolinguals had thicker cortex than the bilinguals. This was also true for left ACC, $F(1, 78) = 6.24$, $p = .02$, left IFG, $F(1, 78) = 14.96$, $p < .001$, right IFG, $F(1, 78) = 9.59$, $p = .003$, left MFG, $F(1, 78) = 8.63$, $p = .004$, and right MFG, $F(1, 78) = 10.15$, $p = .002$. There was no significant language group effect for right ACC, $F(1, 78) < 1$, nor were there any interaction effects, $F(1, 78) < 1$ for each ROI. Means for each ROI as well as the average whole-brain cortical thickness for each group can be found in Table 6.

Table 6.
Mean cortical thickness (mm) for each group within each of the six cortical regions of interest, as well as average thickness across the cortical surface.

	Younger Adults		**Older Adults**	
	Monolingual	Bilingual	Monolingual	Bilingual
Left ACC	2.98 (0.04)	2.90 (0.04)	2.75 (0.05)	2.62 (0.05)
Right ACC	2.86 (0.03)	2.85 (0.03)	2.67 (0.04)	2.62 (0.04)
Left IFG	**2.79 (0.02)**	**2.71 (0.02)**	**2.56 (0.02)**	**2.47 (0.02)**
Right IFG	2.75 (0.02)	2.69 (0.02)	**2.53 (0.03)**	**2.44 (0.03)**
Left MFG	2.70 (0.02)	2.65 (0.02)	**2.45 (0.03)**	**2.36 (0.03)**
Right MFG	2.64 (0.02)	2.59 (0.02)	**2.40 (0.02)**	**2.31 (0.02)**
Avg. Thickness	**2.63 (0.02)**	**2.59 (0.02)**	**2.46 (0.02)**	**2.37 (0.02)**

Note. Numbers in parentheses are standard errors. **Bolded** scores indicate a significant difference ($p < .05$) between groups.

Corpus callosum volume. A 2×2 MANCOVA was conducted to determine if differences in corpus callosum volume existed between the four groups. As with grey matter volume, eTIV was included as a covariate in all analyses. An FDR-corrected significance threshold of $p < .05$ was adopted to account for multiple comparisons.

There was a main effect of age group for only three parcellations of the corpus callosum; the mid-anterior portion, $F(1, 77) = 22.45$, $p < .001$, the central portion, $F(1, 77) = 40.44$, $p < .001$, and the mid-posterior portion, $F(1, 77) = 5.88$, $p = .03$, with younger adults showing greater volume compared to the older adults. No main effects of language group were evident, $F(1, 77) < 1$ for all parcellations; however, there was an interaction between age and language group for the central segment of the corpus callosum only, *F*(1, 77) = 9.87, *p* = .002, such that among the younger adults, monolinguals had greater volume compared to the bilinguals, but among the older adults, bilinguals showed greater volume in the central segment compared to the monolinguals (see Table 7 for group means). Follow-up *t*-tests confirmed that only the difference between the young adult groups was significant, *t*(48) = 2.91, *p* = .006, although the difference between older monolinguals and bilinguals was also trending toward significance, *t*(30) = 1.71, *p* = .10. eTIV was not a significant covariate for any of the effects of interest.

Table 7.
Mean white matter volume (mm^3) for each group within each of the five corpus callosum (CC) parcellations, as well as total CC volume for each group.

	Younger Adults		**Older Adults**	
	Monolingual	Bilingual	Monolingual	Bilingual
CC Anterior	832 (25)	865 (25)	876 (31)	892 (31)
CC Mid-Anterior	649 (24)	596 (24)	475 (31)	508 (31)
CC Central	**701 (23)**	**600 (23)**	457 (28)	517 (28)
CC Mid-Posterior	547 (18)	544 (18)	479 (22)	515 (22)
CC Posterior	954 (27)	976 (27)	1023 (33)	1031 (33)
Total CC Volume	3683 (80)	3581 (80)	3309 (100)	3463 (100)

Note. Means are adjusted due to the presence of the covariate eTIV. Numbers in parentheses are standard errors. **Bolded** scores indicate a significant difference ($p < .05$) between groups.

Exploratory hippocampal volume analysis. Left and right hippocampal volumes were compared between the four groups, with eTIV as a significant covariate (see Table 8 for group means). As with the other GMV comparisons, there was a significant age effect such that older adults had smaller hippocampi bilaterally, *F*(1, 77) = 46.05, *p* < .001 for the left hippocampus and *F*(1, 77) = 36.57, *p* < .001 for the right hippocampus, but there were no significant differences between monolinguals and bilinguals, *F*(1, 77) < 1, nor any interaction effects for left hippocampus, *F*(1, 77) = 1.21, *p* = .27, or right hippocampus, *F*(1, 77) < 1.

Table 8.
Means and (standard errors) from an exploratory analysis examining group differences in bilateral hippocampal volume.

	Younger Adults		**Older Adults**	
	Monolingual	Bilingual	Monolingual	Bilingual
L. Hippocampus	3895 (52)	3953 (52)	3557 (65)	3484 (65)
R. Hippocampus	4017 (68)	4048 (68)	3548 (85)	3579 (85)

Note. Means are adjusted due to the presence of the covariate eTIV.

Control regions. As mentioned previously, the bilateral precentral gyri and postcentral gyri (corresponding to the primary motor and primary somatosensory cortices, respectively) were selected as control regions, since there was no *a priori* reason to expect that these areas should differ with regard to GMV or cortical thickness between the monolinguals and bilinguals. A 2 (age group) x 2 (language group) MANOVA was conducted, and as expected, younger adults had significantly greater volume in these regions than older adults ($p < .001$ for all comparisons). Surprisingly, the bilinguals and monolinguals did differ significantly in the GMV and cortical thickness of their left precentral gyrus; monolinguals had significantly greater volume, $F(1, 78) = 14.15$, $p < .001$ (see Table 9 for group means), and thicker cortex, $F(1, 78) = 8.24$, $p = .005$ (see Table 10 for group means). Monolinguals also displayed thicker cortex than bilinguals in right precentral gyrus, $F(1, 78) = 5.31$, $p = .02$, and left postcentral gyrus, $F(1, 78) = 6.91$, $p = .01$. There were no interaction effects, $p > .10$ for all comparisons.

Table 9.
Mean GMV (mm^3) for each group within each control region.

	Younger Adults		**Older Adults**	
	Monolingual	Bilingual	Monolingual	Bilingual
L. Precentral	14353 (200)	13467 (199)	12943 (249)	12134 (249)
R. Precentral	13881 (250)	13409 (250)	12677 (312)	12231 (313)
L. Postcentral	9643 (175)	9183 (174)	882 (218)	8768 (218)
R. Postcentral	9174 (206)	9261 (205)	8137 (257)	7814 (257)
L. Cuneus	3038 (90)	2926 (90)	2731 (112)	2854 (113)
R. Cuneus	3360 (93)	3369 (93)	3021 (116)	3129 (116)
L. Pericalcarine	2143 (78)	1992 (78)	1869 (98)	1945 (98)
R. Pericalcarine	2254 (84)	2188 (84)	2077 (105)	2233 (105)

Note. Means for GMV are adjusted due to the presence of the covariate eTIV. Numbers in parentheses are standard errors.

Table 10.
Mean cortical thickness (mm) for each group within each control region.

	Younger Adults		**Older Adults**	
	Monolingual	Bilingual	Monolingual	Bilingual
L. Precentral	2.73 (0.03)	2.69 (0.03)	2.53 (0.04)	2.39 (0.04)
R. Precentral	2.68 (0.03)	2.65 (0.03)	2.46 (0.03)	2.36 (0.03)
L. Postcentral	2.13 (0.02)	2.08 (0.02)	2.06 (0.03)	1.98 (0.03)
R. Postcentral	2.13 (0.03)	2.10 (0.03)	1.99 (0.03)	1.92 (0.03)
L. Cuneus	1.87 (0.03)	1.85 (0.03)	1.79 (0.03)	1.70 (0.03)
R. Cuneus	1.91 (0.03)	1.89 (0.03)	1.82 (0.03)	1.76 (0.03)
L. Pericalcarine	1.61 (0.03)	1.62 (0.03)	1.59 (0.04)	1.52 (0.04)
R. Pericalcarine	1.56 (0.03)	1.52 (0.03)	1.56 (0.03)	1.52 (0.03)

Note. Numbers in parentheses are standard errors.

While the supplementary motor area (SMA) and pre-SMA have been implicated previously in bilingual language processing (Abutalebi et al., 2012; Meschyan & Hernandez, 2006), no other studies have mentioned differences between monolinguals and bilinguals in primary motor cortex, which it why it was chosen *a priori* as a control region. In fact, if anything, structural differences might have been expected in the postcentral gyrus, as some previous work (e.g., Olulade et al., 2016) has shown that bilinguals show greater grey matter volume in this region compared to monolinguals. However, I only found differences in cortical thickness of the left postcentral gyrus, not volume, between my bilinguals and monolinguals, with monolinguals displaying thicker cortex in that region. Given my other findings that monolinguals had greater cortical thickness in left ACC, bilateral IFG, and bilateral MFG compared to bilinguals, I wanted to make sure that this finding was not a result of an overall language group confound in the sample. As such, two additional control regions were considered, the cuneus and pericalcarine cortex, both of which are located in primary visual cortex. As with the prior control regions, GMV and cortical thickness was examined in each of these regions bilaterally. There were no significant effects of age group, language group, or interactions in any of these four regions (see Tables 9 and 10 for GMV and cortical thickness means, respectively), signifying no generalized differences in cortical volume or thickness between monolinguals and bilinguals in the present sample.

TBSS Findings

Whole brain analysis. A 2x2 between-subjects ANOVA revealed only a main effect of age, such that younger adults had greater white matter integrity (defined as the measure of FA at each voxel in the mean FA skeleton) across the majority of the FA skeleton compared to the older adults, $p < .05$ (see Figure 8). There were no significant clusters of voxels that differed between bilinguals and monolinguals, nor were there any interaction effects.

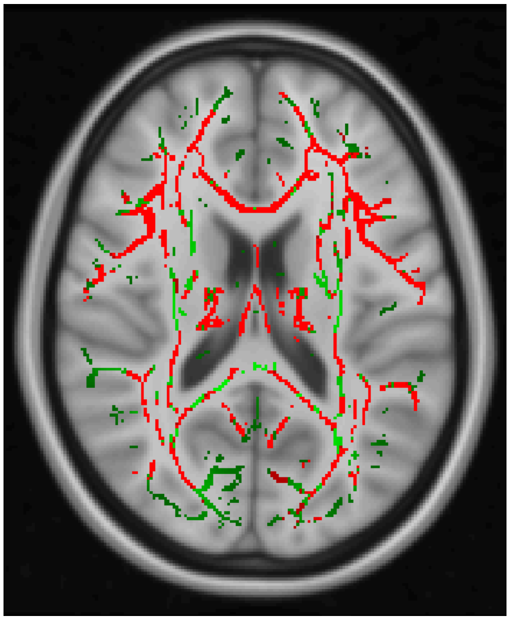

Figure 8. TBSS map projected onto an axial slice of the brain showing the mean FA skeleton (green) for all participants, overlaid with the contrast showing greater FA for younger adults compared to older adults (red signifies $p < .05$).

ROI analysis. I predicted that white matter integrity in tracts that underlie frontal memory regions, such as the cingulum and SLF, as well as the corpus callosum, might show patterns of greater FA for bilinguals compared to monolinguals. To investigate this further, 2x2 between-subjects ANOVAs were conducted for bilateral cingulum and SLF, as well as the genu, body, and splenium of the corpus callosum. Consistent with the whole-brain TBSS analysis, for each of the three corpus callosum ROIs, left cingulum, and bilateral SLF, there was a main effect of age such that younger adults had clusters of greater FA in these regions compared to older adults, $p < .05$ for all. However, there were no differences between monolinguals and bilinguals nor any interactions between age and language group, $p > .10$ for all other comparisons for these ROIs.

Exploratory UF and ILF analysis. Since I was interested in whether hippocampal volume differed between my groups of participants, I thought it was also worthwhile to investigate possible differences in FA in the UF and ILF, since these tracts connect frontal regions with temporal areas that support hippocampal function. As with my other ROI analyses, there was a significant effect of age in the left UF and bilateral ILF, with older adults showing lower FA than younger adults, $p < .05$, but no language group effect and no significant interactions, $p > .10$ for all other comparisons.

Correlations Between White Matter and Grey Matter ROIs

I examined whether structural relationships existed between the grey matter regions of interest and white matter tracts that underlie these cortical areas. As in previous analyses, FA was the dependent measure of white matter integrity. Cortical thickness was chosen as the grey matter measure of interest for these correlations, as past research has shown that changes in cortical thickness and FA are tightly linked (Kochunov et al., 2011; Storsve, Fjell, Yendiki, & Walhovd, 2016; Wang et al., 2009) while grey matter volume and FA are not (Pareek, Rallabandi, & Roy, 2018). As mentioned previously, TFCE thresholding was used to correct for multiple comparisons. Age was included as a covariate in all analyses. There were no significant relationships between grey and white matter ROIs that survived when age was accounted for, $p > .05$ for all regression models. This was true of relationships examined across the entire sample, as well as correlations between grey and white matter done within each language group (e.g., for the bilinguals or monolinguals only).

Because the hippocampus was potentially thought to be implicated in the cognitive processes necessary for resistance to PI, the relationships between hippocampal integrity and FA of bilateral UF and ILF were also investigated as part of an exploratory analysis. Volume was used as the dependent measure for the hippocampus because it is a subcortical structure, and thus cortical thickness cannot be measured. As with the other correlations between grey and white matter, there were no significant relationships between hippocampal volume and white matter integrity above and beyond what is accounted for by age.

Summary of Structural Findings

As expected, age effects were common across each of the grey and white matter regions of interest, with younger adults showing greater grey matter and white matter volume, as well as cortical thickness. Of the two grey matter dependent measures, cortical thickness appeared to be more sensitive to differences between bilinguals and monolinguals, with monolinguals displaying thicker cortex in left ACC, bilateral IFG, and bilateral MFG across both age groups. However, the exploratory analysis of the hippocampus yielded no differences when compared by language group.

With regard to the white matter indices, an age effect was also present such that younger adults showed greater FA across many of the fiber tracts common to all participants. However, there were no group differences in FA between bilinguals and monolinguals, nor any interactions for either the whole-brain or ROI-based TBSS analyses, which suggests that knowing two languages does not alter the integrity of white matter fibers, at least with regard to restriction of water diffusion. In addition, there were no significant relationships between grey and white matter ROIs above and beyond what age accounted for.

However, younger monolinguals displayed greater volume in the central segment of the corpus callosum compared to the young bilinguals, and the opposite was true for the older adults (bilinguals displayed greater volume). It seems that white matter volume stays fairly constant for the bilinguals while being significantly impacted by age in the monolinguals, though it is difficult to make strong claims given the cross-sectional nature of the dataset. This suggests that knowing two languages does preserve some aspects of white matter integrity, perhaps with regard to characteristics such as fiber count or fiber thickness. What has not yet been examined to this point are the relationships between brain structure and the behavioral outcomes, which is what the following section will focus on.

Brain-Behavior Correlations

I sought to discover noteworthy relationships between brain structure of the participants and their cognitive performance or bilingual experience. All relationships reported herein were subject to an FDR or TFCE correction for multiple comparisons.

Resistance to PI tasks. Although there were no apparent differences between bilinguals and monolinguals with regard to inhibitory ability on either memory task, it was still unclear whether performance on the directed forgetting and release from PI tasks predicted individual differences in brain structure within the sample, and whether these relationships would prove stronger among bilinguals or monolinguals.

Grey matter. I correlated each of the dependent behavioral measures (from directed forgetting: TBR words recalled and TBF words recalled; from release from PI: buildup of interference, release from interference, buildup of intrusions, and release from intrusions) with GMV and cortical thickness of each of the six cortical ROIs (bilateral ACC, IFG, and MFG) across the entire sample. Significant relationships with the grey matter measures only emerged for buildup and release from intrusions. Buildup and release from intrusions are derived from a difference between List 3 intrusions and intrusions on List 1 or List 4; therefore, I decided to use the number of List 3 intrusions as the primary behavioral measure. Cortical reduction initially appeared to be a predictor of greater interference on the release from PI task in the grey matter regions of interest. However, when each of these relationships was tested in a regression model with age as a covariate, none remained significant ($p > .50$), suggesting that older age is driving both greater behavioral interference and reductions in volume and thickness. The same was true when the regressions were run on each language group separately ($p > .05$).

Corpus callosum. Across the whole sample, the number of List 3 intrusion errors was correlated with volume of each of the five parcellations of the corpus callosum. There was a significant, positive relationship between List 3 intrusions and the posterior section of the corpus callosum, $r(80) = .38$, $p < .001$. Upon closer inspection of the scatterplot of the data, there was one participant (monolingual younger adult) with 6 intrusion errors on List 3, whereas the rest of the sample had between 0-4 errors. The correlation was re-run excluding this participant, and the relationship was no longer significant according to the FDR-adjusted *p*-value, $r(79) = .24$, $p = .17$.

TBSS. Across the entire sample, there were no significant relationships between whole-brain FA and any dependent measures from the directed forgetting or release from PI tasks, $p > .05$ for all comparisons. When the analyses were re-run on the bilinguals and monolinguals separately, there were also no significant findings, $p > .05$ for all comparisons. Age was included as a covariate in all aforementioned analyses; thus, these results suggest that whole-brain white matter integrity does not predict resistance to PI abilities above and beyond what age predicts.

I then followed up with correlations examining the relationships between individual tracts of interest and various behavioral measures. As noted above, age was included as a covariate for all subsequent analyses. Across the whole sample, there was a negative correlation between TBF words recalled from the directed forgetting task and splenium FA, such that better performance (fewer TBF words recalled) was related to higher FA, $p = .05$. This relationship also held when examining the bilinguals only, $p = .03$. When examining the monolinguals by themselves, there was no relationship between TBF recall and splenium FA, $p = .50$, but there was a negative relationship between TBF recall and bilateral UF FA, $p = .01$ for both left and right UF. These data appear to suggest that the monolinguals and bilinguals could be relying on different white matter tracts to support resistance to PI-related memory processes.

Of the release from PI task outcome variables, buildup of interference for the whole sample was negatively related to both left and right UF FA (for the left UF, $p = .008$, for right UF, $p = .03$) suggesting that increasingly poorer recall performance over the first three lists is linked to less water diffusion restriction in bilateral UF, which are tracts known for connecting the prefrontal regions associated in resistance to PI (e.g., the IFG) to parts of the anterior temporal lobe including parahippocampal areas. When the sample was divided by language group, this relationship was still present for the monolinguals ($p = .03$ for left UF, $p = .02$ for right UF), but not the bilinguals. A negative relationship among all participants was also present between release from interference and right SLF FA, $p = .004$, which implies that the greater the improvement in recall performance between List 3 and List 4 (synonymous with saying the lower recall performance was on List 3), the poorer the white matter integrity is in the participant's right SLF. This relationship was also significant when the same correlation was calculated for just the bilingual sample, $p = .01$.

Flanker task. I was interested in whether performance on the flanker task, a test of resistance to perceptual distractor interference, might relate to brain structure in ways that differ from the resistance to PI measures. There were no relationships present between the flanker interference effect and any of the ROI measures of grey matter volume, cortical thickness or callosal volume. There was also no significant relationship between FA and the flanker effect.

Bilingual experience variables. I also examined whether aspects of the bilingual experience, particularly language proficiency, frequency of use, and AoA, would be predictive of cortical volume and thickness, after accounting for age. Among the bilinguals, English proficiency (speaking, reading, writing, and understanding) did not correlate with grey matter volume in any of the six ROIs. English AoA was also not related to volume or thickness for any cortical ROIs. With regard to Spanish, proficiency and frequency of use were not related to any of the six cortical ROIs. Spanish AoA significantly predicted left IFG volume, standardized $\beta = -.28$, $t(39) = -2.23$, $p = .03$, and marginally predicted right MFG volume, standardized $\beta = -.27$, $t(39) = -1.96$, $p = .06$. Therefore, it appears that the older participants are when they learn Spanish, the smaller certain cortical regions are that are important for bilingual language use and resistance to PI, above and beyond any changes in grey matter one might expect as a function of age.

I also assessed whether any of the bilingual experience variables correlated with the callosal ROIs as defined by Freesurfer. There were no significant relationships between proficiency, AoA, or language use and volume of any of the parcellations of the corpus callosum.

In addition to considering the relationships between the bilingual experience variables and grey matter regions of interest, I also ran bivariate correlational analyses with the TBSS data to determine whether any clusters of voxels along the FA skeleton correlated significantly with a proficiency composite (the average of speaking, reading, writing, and understanding), the MINT, or semantic or letter fluency scores. Across the whole sample, FA was not associated with any measures of English proficiency or fluency, $p > .10$ for all relationships, and the same was true for measures of Spanish proficiency and fluency among the bilinguals, $p > .40$ for all relationships. Correlations computed between individual tracts of interest and bilingual experience variables also yielded no significant relationships, $p > .05$ for all.

Summary of brain-behavior correlations. In sum, white matter integrity predicted several outcome measures from the directed forgetting and release from PI tasks across the entire sample and for each language group separately. For example, while FA did not predict TBR recall performance, it did predict TBF recall. Interestingly, the tracts that predicted TBF recall differed for monolinguals and bilinguals. FA of bilateral UF, a tract typically implicated in memory processes, negatively predicted TBF recall performance for the monolinguals, whereas splenium FA was negatively associated with TBF recall for the bilinguals. In the release from PI task, it appears that the monolinguals implicate the UF, whereas the bilinguals may be relying on the SLF more. However, grey matter volume and thickness did not predict behavioral performance above and beyond age, suggesting that white matter integrity might be subject to less deterioration as a function of aging compared to grey matter.

Since brain structure appears to be fairly predictive of behavioral performance for the bilinguals, it makes sense that certain factors characterizing the bilingual participants' Spanish maintenance might also be related to neural indices. Indeed, the longer the bilinguals have known Spanish, the greater their GMV in certain ROIs. However, these bilingual experience factors do not seem to have any association with white matter volume or integrity measures, unlike the behavioral tasks.

Additional Exploratory Analyses

I was interested in the variables that might predict performance on each of the resistance to PI tasks, and thus conducted simultaneous multiple regressions in order to determine which demographic, cognitive, or neural measures play a role in participants' memory performance. The outcome variable for the directed forgetting task was proportion of TBR words recalled. Number of TBF words recalled was not considered as an outcome variable since in general all participants demonstrated intact inhibition (low TBF recall scores) and there was not a great deal of variability amongst participants. The outcome variable for the release from PI task was number of List 3 intrusions, as this variable appears to be the most sensitive predictor of resistance to PI abilities from this particular task. Data from the entire sample was included in the regression analyses.

Table 11 shows the β-weights and t-values for each variable in the model predicting directed forgetting performance (Model 1), while Table 12 displays the β-weights and t-values for each variable in the model predicting release from PI performance (Model 2). Predictors were chosen based on their relevance to the research questions (e.g., the predictors “age” and “language group”) or because of strong relationships between the predictor and outcome variable exhibited in prior analyses (e.g., right IFG and MFG volume with List 3 intrusions). Language group was modeled as a dichotomous variable in both regression equations, while all other variables were modeled continuously. When appropriate, variables were centered for ease of interpretation.

Overall, Model 1 was significant, $F(4, 77) = 3.99$, $p = .005$. The only variable that significantly predicted proportion of TBR words recalled correctly was MoCA score, $p = .02$, although age ($p = .07$) and List 3 intrusions ($p = .08$) were both trending towards significance. Ultimately, the model only explained about 17.2% of the variance in TBR recall, so it is quite possible that other factors that were not considered might provide better explanatory power to the model.

Model 2 was also significant, *F*(6, 77) = 6.12, $p < .001$. TBR recall scores were predictive of number of List 3 intrusions, $p = .008$, as were right IFG volume, $p = .005$, and eTIV, $p = .001$. Only right IFG and MFG volumes were included in the model because they were strongly related to volumes of their homologues in the left hemisphere ($r \geq .70$ in both cases), and the right IFG and MFG showed stronger bivariate relationships with List 3 intrusions than their left hemisphere counterparts. This model explained approximately 32.9% of the variance in number of List 3 intrusions, showing slightly better explanatory power compared to Model 1.

Table 11.
Predictors of TBR words correctly recalled from the directed forgetting task.

Predictors	Standardized β	*t*-value
Age	-0.21	-1.84
Language Group	-0.03	-0.29
MoCA	**0.25**	**2.31**
List 3 Intrusions	-0.20	-1.80

Note. **Bolded** values indicate a significant predictor at $p < .05$.

Table 12.
Predictors of number of List 3 intrusions in the release from PI task.

Predictors	Standardized β	*t*-value
Age	-0.24	-1.26
Language Group	-0.18	-1.85
TBR Recall	**-0.28**	**-2.73**
Right IFG Volume	**-0.56**	**-2.93**
Right MFG Volume	-0.30	-1.86
eTIV	**0.48**	**3.36**

Note. **Bolded** values indicate a significant predictor at $p < .05$.

Chapter 4

Discussion

Whether or not being bilingual provides any advantages in the domain of memory performance, and specifically resistance to proactive interference, is a topic that has been largely ignored in the bilingualism literature thus far. This research aimed to bridge the gap between studies examining bilingual behavior and studies investigating the bilingual brain, by incorporating behavioral tasks, structural MRI, and DTI into a single experimental paradigm. By utilizing a cross-sectional approach, I was able to assess differences between younger and older bilinguals and monolinguals with regard to cognitive performance as well as the integrity of the neural structures underlying these cognitive abilities.

In general, no memory-related behavioral differences emerged between bilinguals and monolinguals. However, differences in brain structure were present in both grey and white matter. While there were no language group differences with regard to grey matter volume, monolinguals displayed thicker cortex in left ACC, bilateral IFG, and bilateral MFG, regardless of age. In addition, although no language group differences were evident in measures of FA, there was a significant interaction between age and language group for the central corpus callosum, such that monolinguals had greater volume among the young adults, but less volume among the older adults.

Brain structure also predicted behavioral performance in unique ways for the two language groups. FA of the splenium was negatively associated with directed forgetting performance (TBF recall) for the bilinguals, while FA of bilateral UF was negatively associated with TBF recall for the monolinguals. Finally, certain bilingual experience variables such as Spanish understanding and frequency of Spanish use (during free time) appear to be significant predictors of resistance to PI task performance, while Spanish AoA was uniquely related to brain structure.

Evaluation of Predictions

My predictions regarding the older adult sample were derived from the comparison of two different theoretical frameworks. The first was the brain reserve hypothesis, which suggests that some individuals have brains that are more resilient to the effects of aging, resulting in slower rates of neural decline than more “typical” aging brains. Cognition will remain intact until some atrophic threshold is reached; at that tipping point, both brain structure and the cognitive processes it supports begin to decline in tandem. On the other hand, the cognitive reserve hypothesis suggests that brain and behavior do not have to decline in synchrony; instead, this hypothesis posits that cognitive performance can remain intact despite brain atrophy, and that cognition will remain buoyant as a function of other cognitively demanding activities that the individual has been subject to throughout their life. The suggestion has been made that using two languages on a regular basis might act as one of these reserve mechanisms that preserves cognition during aging (Gold et al., 2013; Luk et al., 2011a).

Resistance to PI tasks. When considering behavioral performance, the only significant group difference on the directed forgetting task was better performance for TBR words amongst the younger adults compared to the older adults. This was to be expected as memory performance typically declines across the lifespan (Hedden &

Gabrieli, 2004). On directed forgetting tasks, older adults tend to remember significantly more TBF words than the younger adults, which is often interpreted as a sign of poorer attentional control and worse resistance to PI (Campbell et al., 2012; Weeks & Hasher, 2018). However, this pattern of results was not seen in the present study, and there are several possible reasons for this. First, the amount of time allocated for the distractor between encoding and recall might have been too long, resulting in more forgetting of the words than anticipated. Another possibility might be that the distractor task (drawing and labelling a map of the United States) was too difficult. However, this distractor has been used in prior directed forgetting studies (Sego et al., 2006), and for an even longer duration (five minutes in the study done by Sego et al., whereas in the present experiment participants only completed the distractor task for three minutes).

Therefore, it seems that the most likely explanation may be that the "forget" condition in the present study did not provide enough cognitive load or distraction to induce substantial differences in performance between the older and younger adults. Weeks and Hasher (2018) suggest that older adults generally display worse performance on directed forgetting tasks because they experience greater "attentional broadening" and are more easily distracted than young adults. In their previous work, they found that older adults remembered more TBF items when multiple stimuli were presented at once (e.g., a picture with a word overlaid on top) and they are told to only remember one item (such as the picture) while ignoring the other item (the word). Thus, introducing a condition in which greater attentional resources are required to sort between the relevant and irrelevant stimuli might induce larger behavioral differences between younger and older adult participants, especially for the “forget” condition.

On the release from PI task, the younger adults outperformed the older adults, particularly with regard to intrusions; while the older adults experienced significant buildup of intrusions across Lists 2 and 3, young adults did not experience this same effect. Again, no differences on either correct recall or intrusion errors emerged between the bilingual and monolinguals for either age group.

For both the directed forgetting and release from PI tasks, there was no difference in performance between the older bilinguals and monolinguals; they performed virtually identically, regardless of language experience. In addition to similar performance on both tasks, the older adults were also matched cognitively, as evidenced by comparable MoCA scores. However, when examining the cortical brain regions that support resistance to PI task performance, it became evident that older monolinguals had significantly thicker cortex than the older bilinguals, particularly in bilateral IFG and MFG. This pattern of findings supports the cognitive reserve approach rather than the brain reserve hypothesis, because matched cognition between groups and comparable performance on various behavioral tasks is coupled with cortical thinning in the bilingual participants (Stern, 2009). Thus, when cognitive status is held constant, the bilinguals appear to be achieving similar behavioral performance outcomes compared to the monolinguals, even with less brain matter to support cognitive processes. A similar pattern of results has been seen before (Gold et al., 2013), such that bilingual and monolingual older adults were matched on a series of neuropsychological tasks, but the bilinguals demonstrated less white matter integrity. With regard to cortical indices, the researchers only looked at grey matter volume and not cortical thickness, so it is possible that their bilinguals might have also been experiencing greater cortical thinning compared to the monolinguals. Results such as these, in corroboration with the present findings, suggest that knowing a second language does indeed provide protective benefits to older adult bilinguals, though they might not be evident when examining behavior by itself. This is why it is important, when possible, to examine both brain and behavior in tandem to uncover these hidden links between cortical structure and cognitive performance.

While cognitive reserve explains the grey matter differences between older bilinguals and monolinguals, the white matter data actually suggest a pattern more consistent with brain reserve in the older adults. Though group comparisons did not yield significant differences in FA between older bilinguals and monolinguals (which differs from past work that has found greater FA in older bilinguals; Luk et al., 2011a), correlational analyses showed that bilinguals often exhibited significant relationships between FA and behavioral indices, with greater FA typically indicating better resistance to PI performance. It is possible that the present findings differ from the study done by Luk and colleagues due to differences inherent to the samples; in the current study the two languages groups were matched cognitively, but in the Luk et al. study it is unclear whether the same was true. The authors note that the two groups were comparable on neuropsychological performance but do not provide any means or statistics for task performance for the two groups. Alternatively, variables characterizing the bilingual experience could differ between the two samples. Luk and colleagues state that the bilinguals had been using two languages regularly since prior to age 11, but it would be worth considering how self-rated proficiency and their frequency of L1 and L2 use compares to the bilinguals in the current study. In the present study, in the few instances where both monolinguals and bilinguals showed associations between greater white matter integrity and cognitive performance, different tracts were implicated in each group, suggesting that bilinguals and monolinguals could be relying on different neural resources in order to maintain cognitive performance. Additionally, bilingual older adults displayed greater volume in the central segment of the corpus callosum compared to monolinguals. Taken together, all of these results indicate that the older adult bilinguals are exhibiting evidence of both brain reserve (in the white matter) *and* cognitive reserve (in the grey matter) as a function of knowing two languages.

To date, only a few prior studies have found evidence for both brain and cognitive reserve within the same participants, and these studies were not focused on the influence of bilingualism, but rather how both mechanisms protect patients diagnosed with various neurodegenerative diseases such as multiple sclerosis (Sumowski et al., 2014) or Alzheimer’s disease (Groot et al., 2018). Indeed, there has only been one prior study demonstrating patterns of both cognitive reserve and brain reserve within the same group of bilingual participants (Duncan et al., 2018). While certain brain regions were larger in bi- or multilinguals diagnosed with MCI or Alzheimer’s compared to similarly diagnosed monolinguals, other cortical areas, such as parahippocampal regions, showed more atrophy amongst the bi/multilinguals in comparison to the monolinguals. The present findings differ from this previous work in two important ways: first, the study by Duncan and colleagues was focused on the cognition and brain structure of bilinguals diagnosed with varying degrees of cognitive impairment; the current study only tested cognitively healthy bilinguals. Second, the study by Duncan et al. (2018) only focused on grey matter regions, whereas my findings suggest an independence of cognitive and brain reserve mechanisms as a function of grey versus white matter. To my knowledge, there are no other studies that have shown this pattern of results in the same group of individuals. The present study is the first of its kind to thoroughly investigate how cognitive performance relates to both grey and white matter integrity in older bilinguals and has yielded novel findings that can aid in better understanding how bilingual and monolingual brains differ in old age.

Turning attention to the younger adults, there were no significant differences between the monolingual and bilingual groups on the directed forgetting task or the release from PI task. As mentioned previously, differences in behavioral performance between cognitively healthy young adult bilinguals and monolinguals are rare, since one's early twenties can be considered the "peak" age for various cognitive abilities including inhibition and resistance to PI. Additionally, in the limited research that has been done to date on resistance to PI performance in bilinguals, it has been suggested that significant differences between bilingual and monolingual young adults emerge only if vocabulary knowledge is included in the analysis as a covariate (Bialystok & Feng, 2009), since bilinguals tend to have smaller vocabularies in each language compared to a monolingual's vocabulary size. However, vocabulary performance (based on English MINT score) was not a significant predictor in any of my analyses, likely because all of the bilinguals in my study self-reported high proficiency in both languages. Therefore, the lack of cognitive differences is not surprising, nor was it hypothesized that behavioral differences would be expected among the young adults. The only distinctions that emerged unique to the young adults were with regard to brain structure: a difference in average thickness across the entire cortical mantle, in left IFG thickness, and in volume of the central segment of the corpus callosum. In each of these cases, young monolinguals displayed greater thickness and volume than the young bilinguals did. This is the opposite of what other researchers such as Klein and colleagues (2014) have found; they actually saw greater left IFG thickness in early bilinguals compared to monolinguals.

One possibility for these divergent findings could be due to differences in language experience between the bilingual samples recruited for each study. In my study, nearly all of the bilinguals were highly proficient early sequential bilinguals who learned one language (typically Spanish) from birth and began learning their second language by the age of five. While the participants from Klein's study that exhibited greater left IFG thickness were also early sequential bilinguals, their proficiency was not as high (mean self-report rating = 5.4/7; Klein et al., 2014). It has been proposed elsewhere (Pliatsikas, 2019) that alterations to cortical grey matter are most prevalent during the initial learning stages of second language acquisition, and in contexts where participants are not continually immersed in their L2 environment. Although the participants in the study by Klein and colleagues were from Montreal, a bilingual city, it is likely that the participants varied quite a bit with regard to their amount of exposure to and immersion in their L2, as evidenced by lower proficiency scores in the L2. In the case of my participants, they have been immersed in their L2 language (English) for the majority of their lives and in many instances it has become their dominant language; thus, it is possible that any cortical changes that might have been associated with learning a second language already went through a renormalization period that appears to be prevalent once bilinguals become highly proficient in both languages and use both on a regular basis (Pliatsikas, 2019).

It is interesting that the present data suggests that the monolingual young adults are showing larger or thicker brain structures. One hypothesis that has been suggested previously for explaining patterns of thinner cortex, which is what the young adult bilinguals are displaying, is the notion that underlying white matter expands throughout development and pushes up like a balloon against the cortex, stretching and subsequently thinning the outer layer of grey matter (Hogstrom, Westlye, Walhovd, & Fjell, 2012; Aleman-Gomez et al., 2013). While there were no differences between young adult monolinguals and bilinguals with regard to FA, FA is only a measure of water restriction, and does not necessarily reflect other characteristics of white matter such as axon diameter or amount of myelination that could affect its volume, for example (though see Wu et al., 2014).

Interestingly, the results reported herein are very much in line with the Dynamic Restructuring Model, a recent theory proposed by Pliatsikas (2019) that strives to make sense of the seemingly disjointed and disparate findings in the literature surrounding the bilingual brain. He proposes three stages of change that the brain goes through in the lifelong process of learning and maintaining a second language. The first is *initial* *exposure*; this stage encompasses the grey matter changes that are most typically seen when individuals are learning a second language. In the second stage, *consolidation*, these grey matter alterations renormalize, likely due to pruning that occurs as a result of greater efficiency of the regions and networks necessary for maintaining and controlling use of one's two languages (Pliatsikas, 2019). Pliatsikas also suggests that these efficient connections that remain after learning could be the same connections that retain their integrity once age-relate cortical decline begins to set in, and notes that the development of some of these efficient connections might be occurring in the white matter. This might be why white matter differences such as increases in FA are more prevalent in bilinguals with greater experience. Stage 3, or the *peak efficiency* stage, is less defined, with Pliatsikas suggesting that one needs to conduct longitudinal examinations of bilinguals across their lifetime in order to truly understand when bilingual brain structure is at its peak optimization and how variations in language experience dynamically shape the brain over time.

As there were no instances in my sample where grey matter volume or cortical thickness were greater in the bilinguals compared to monolinguals, the Dynamic Restructuring Model would posit that the bilinguals as a whole had already moved through Stage 1 and entered into Stage 2. While in the older adults the reduced cortical thickness among the bilinguals is likely due to the natural progression of aging, in the young adults, thinner cortex among the bilinguals could be evidence of greater network efficiency, particularly within the underlying white matter. Indeed, although there were no group differences in FA between the bilinguals and monolinguals, greater white matter integrity in several tracts of interest was associated with better behavioral performance for only the bilinguals, which Pliatsikas would likely argue is a function of the experience of continually juggling two languages. No conclusions about Stage 3 can be drawn from the present study since no longitudinal data was collected. Thus, it appears the findings herein do in fact corroborate some tenets of the Dynamic Structuring Model (Pliatsikas, 2019).

Flanker task. In the present study, bilinguals were slower to respond on both congruent and incongruent trials compared to monolinguals, regardless of age, and there were no significant differences between groups with regard to the flanker effect. These response time findings appear to be an exception to the pattern mentioned previously of bilinguals and monolinguals demonstrating similar cognitive performance, and is contradictory to prior studies such as the one done by Abutalebi et al. (2015b) that found older bilinguals outperformed monolinguals (by responding more quickly) on both trial types, or work done by Luk, De Sa, and Bialystok (2011b) which found a smaller flanker effect in bilinguals compared to monolinguals. The study by Luk and colleagues also discovered a positive correlation between the flanker effect and second language AoA, such that the younger one was when they acquired a second language, the smaller their flanker effect.

This raises some questions about why this obvious difference in performance occurred between prior examinations of flanker task performance and the present findings. One reason could be due to task-related differences. For example, it has been suggested previously that the bilingual advantage is only evident in conditions that involve high levels of conflict monitoring (e.g., an even distribution of congruent and incongruent trials; Costa et al., 2009). In the present study, two-thirds of the trials were congruent while only one-third were incongruent; both of the studies mentioned above (Abutalebi et al., 2015b; Luk et al., 2011b) had equivalent numbers of congruent and incongruent trials. Perhaps a higher proportion of incongruent trials (e.g., 50%) might have induced more monitoring and thus a smaller flanker effect in my bilingual sample.

Additionally, while the flanker task has been commonly employed to examine differences in resistance to perceptual distractor interference in studies comparing bilingual and monolingual cognition, there have been several failures to replicate a bilingual advantage (see Hilchey & Klein, 2011 for a review; Paap & Greenberg, 2013). The task was included in the present study in order to test a type of inhibition that has been shown to not share any variance with the primary construct of interest, resistance to PI, and determine whether performance on the two types of tasks was at all related (see the following section). However, because the flanker task has historically not shown strong differences between bilinguals and monolinguals, the flanker findings reported herein should be interpreted with caution and not used to infer any sort of cognitive differences between the two groups.

Relationships Between Tasks

In 2004, Friedman and Miyake published a seminal study in which they used a latent variable analysis to determine which types of inhibition were related, and which could be considered separable and unique constructs. From their analysis, they concluded that prepotent response inhibition and resistance to distractor interference shared much of the same variance, but that resistance to proactive interference shared virtually no variance with either of the other two variables. Based on these results, I expected that my two resistance to PI tasks, directed forgetting and release from PI, would be correlated, whereas there would be no relationship between these tasks and the flanker task, which is considered a resistance to distractor interference task.

As expected, the outcome variable measured for the flanker task, the flanker effect, was not related to the dependent measures of either the directed forgetting or resistance from PI tasks, supporting Friedman and Miyake's conclusions that resistance to distractor interference and resistance to proactive interference were two separate constructs. Surprisingly, the outcome measures of the directed forgetting and release from PI tasks were also not significantly related when considering the data from the entire sample. However, when the correlations were considered separately for monolinguals and bilinguals, the bilinguals did show significant negative relationships between TBR word recall and buildup of intrusions, as well as TBR word recall and release from intrusions. These findings suggest that better TBR word retrieval is related to less interference on the release from PI task, for the bilinguals only.

In the original study by Friedman and Miyake (2004), they gave participants three different tasks to test each of their constructs. For the resistance to PI variable, participants completed a Brown-Peterson variant, which is very similar to the release from PI task used in the present study, an AB-AC-AD task, and a cued recall task. Though not used by Friedman and Miyake, directed forgetting has been touted in past literature as a measure of resistance to PI, especially in studies examining inhibitory declines in older adults (Hogge et al., 2008; Titz & Verhaeghen, 2010; Weeks & Hasher, 2018; Zacks et al., 1996; though see Bissett et al., 2009, for a directed forgetting study done with younger adults). Interestingly, I have not been successful in finding a study that has included both release from PI and directed forgetting tasks as measures to test resistance to PI in the same sample. Therefore, it is unclear whether the directed forgetting task used herein is truly measuring resistance to PI in the same way that the release from PI task is.

It is also important to note that there are two different versions of the directed forgetting task. The version employed in the present experiment was an item-method version, where participants were shown a remember or forget cue after the presentation of each individual word. In a list-method version of the task, participants see an entire list of words and are told at the end of encoding they should either remember or forget that list. The item-method version was chosen for this study because it tends to show larger age effects (Titz & Verhaeghen, 2010). However, Sego and colleagues (2006) failed to find an effect of greater TBF recall among the older adults in their study (they used an item-method version) compared to the younger adults. Instead, all participants were exhibiting intact inhibitory abilities, as evidenced by the fact that neither group recalled more than 10% of the TBF words, with levels of TBF recall nearly identical to what I found in my sample. One might hypothesize that participants are falling prey to demand characteristics, and purposely not recalling TBF words in spite of the experimenter's urging. However, past research has shown that even if participants are offered a monetary incentive to recall more TBF words, they fail to do so, suggesting that participants truly are forgetting these words (MacLeod, 1999). Another possible explanation could be that each word in the item-method version receives less processing time than words in the list-method version (Woodward, Park, & Seebohm, 1974; Basden, 1996). In an item-method task, participants are cued to forget words after only about three seconds of rehearsal, which would make forgetting quite easy; in a list-method version, some of the items may be rehearsed for upwards of a minute, making these items less susceptible to forgetting. Therefore, it is possible that a list-method version of the directed forgetting task might yield more similar results to, and be more strongly correlated with, a release from PI task, since each word from a list is rehearsed for a longer period of time and could be more susceptible to being remembered, even under explicit "forget" orders.

So, knowing that the directed forgetting and release from PI tasks, at least the versions used in the present experiment, might not measure exactly the same inhibition construct, why is there a relationship present among task outcomes when considering the bilingual data separately from the monolingual data? Both buildup of and release from intrusions are indicators of how much proactive interference is present across each list, and lower scores on each of these measures would be considered indicative of better inhibition. On the other hand, TBR recall and TBF recall appear to be measuring two different memory processes; intentional memory versus incidental memory, respectively. Therefore, one possible explanation could be that for the bilinguals, inhibitory abilities and intentional memory performance are more tightly linked than for monolinguals. Perhaps using two languages results in more frequent utilization of memory resources (e.g., first remembering, and then selecting, which language to speak in a particular context), and thus requires increased connectivity between the regions underlying these processes – something that the monolinguals would not need to maintain.

Although bilinguals seemed to show a stronger coupling between performance on the resistance to PI tasks than monolinguals, the monolinguals demonstrated a stronger relationship between directed forgetting and MoCA performance. This was seen as a function of a significant interaction effect between language group and MoCA performance (as a reminder, the sample was divided into "high" and "low" MoCA performers) on proportion of TBR words recalled. Low MoCA-scoring monolinguals performed significantly worse than the high MoCA-scoring monolinguals on TBR recall, whereas there was virtually no difference in performance amongst the bilinguals regardless of whether they performed in the "high" or "low" range on the MoCA. While the MoCA was only intended for use as a screening measure to ensure that all participants were cognitively healthy, I became interested in how MoCA performance might relate to performance on my behavioral tasks since several of the questions on the MoCA test various aspects of memory. As mentioned previously, TBR recall is measuring intentional declarative memory, as are several parts of the MoCA; for example, the clock drawing and animal naming components require semantic memory, and the delayed recall task necessitates the use of episodic memory. These three tasks together make up a significant portion (11 out of 30 points) of the MoCA score, so it makes sense that the overall MoCA and TBR scores would be correlated. However, this relationship was not present for the bilinguals; instead, TBR recall was independent of MoCA score. These findings suggest that knowing more than one language may provide a protective effect for intentional memory abilities regardless of cognitive status. For example, one might expect that monolinguals with MCI or Alzheimer's would see a decline in long-term memory performance, but it is possible that a bilingual with MCI or Alzheimer's would maintain performance on the same memory task. Of course, further testing would need to be done to confirm this hypothesis.

Importance of the Bilingual Experience

At the outset of this study, one of my research questions involved addressing which aspects of the bilingual experience (e.g., proficiency, AoA, frequency of use) would predict resistance to PI task performance. I expected that each would relate to memory abilities to some degree, but that proficiency would be the strongest predictor, since vocabulary knowledge appeared to be important for moderating release from PI performance in prior research examining resistance to PI in bilinguals (Bialystok & Feng, 2009). However, the majority of the bilinguals recruited for this study (both young and old) were highly proficient in both English and Spanish, and 96% of the sample acquired both languages by the time they were five years old. Therefore, there was a severe restriction of range in the data for several of these variables that I had been interested in, limiting my ability to use them in any sort of meaningful correlational analyses.

However, the older adult bilinguals were more diverse in their self-ratings than the bilingual young adults, and when their data were examined separately some interesting relationships emerged. Self-reported frequency of Spanish use in one's free time and Spanish understanding (part of the proficiency composite) were the two strongest predictors of resistance to PI performance for the older sample, and showed that those who use Spanish more and better understand Spanish had a smaller improvement in correct recall between Lists 3 and 4. However, it became clear that this smaller difference between List 3 and List 4 was not due to lack of PI release on List 4, but rather less buildup of interference on List 3. Thus, the data suggest that better maintenance of the L1 (in the case of the majority of the bilinguals, Spanish) coupled with strong L2 (English) proficiency appears to be associated with less proactive interference as a function of better inhibition.

This conclusion is supported further by the neural data. In particular, Spanish AoA was negatively associated with grey matter volume above and beyond what could be accounted for by age. Not only is cognitive performance supported by longer and well-maintained Spanish use among the bilinguals, but the longer one has known Spanish also influences the structural indices that underlie resistance to PI abilities.

Limitations and Future Directions

While a few limitations of the current study and suggestions for future research have already been addressed in the preceding sections, there are still several other points worth mentioning. First, this study utilized a cross sectional design, which limits the ability to draw strong conclusions about changes to the participants' brain structure or resistance to PI abilities over time. In the future, it would be ideal to follow both bilinguals and monolinguals longitudinally in order to assess how patterns of neural or cognitive alteration might differ between groups, though this would of course require a great deal of time and resources.

Next, although the number of participants in the study was satisfactory, especially for one involving neuroimaging, the monolingual versus bilingual older adult comparisons did suffer from a smaller sample size with only 16 participants in each group. One reason that not as many older adults were included in the study, compared to young adults, was primarily due to immense difficulty recruiting older bilinguals. Older adult recruitment was initially done solely through an aging database shared by UC Riverside faculty who conduct research with older populations. However, it soon became clear that nearly all of the older adults who volunteered to be part of the database were monolingual, so it became necessary to advertise the study to the surrounding community via flyers posted in coffee shops, grocery stores, and community centers. The majority of these calls for participants went unanswered and could be due to several factors: a general lack of interest in participating, the inability to come to campus during regular business hours because of work or family obligations, or a wariness surrounding research that may exist in the older, Spanish-English bilingual population in Southern California. Therefore, it seems that more efforts should be made to educate this population about the merits of university research, encourage their participation in the future, and be accommodating to their schedules in order to allow them to participate more easily.

As mentioned previously, there was a lack of linguistic diversity in the present sample; all the bilinguals were highly proficient and nearly all would be considered early bilinguals, acquiring both languages before the age of five. In addition, the majority of the bilinguals in this study were heritage speakers, and while in general they learned Spanish first, they identified as more proficient in English compared to Spanish.

Therefore, it is difficult to generalize the present findings to bilinguals that might have been exposed to different linguistic experiences, such as late acquisition of a second language or living in an immersive environment where the bilingual is generally required to speak the less dominant language. Additionally, I only tested Spanish-English bilinguals, so it is unclear how bilinguals of other languages might perform on these tasks, or whether multilinguals (those who know at least three languages) would show differing patterns of performance.[4] In future iterations of this study, I would like to recruit participants with diverse linguistic backgrounds, and measure how variables such as second language AoA influence resistance to PI abilities.

It is also important to note that while language experience variables such as proficiency and AoA did not differ between the bilingual younger and older adults, one variable, frequency of language use in the home, was significantly different between groups, with the younger adults using Spanish in the home much more frequently than the older adults (64% v. 22%, respectively). This stark difference between groups signifies an obvious cohort effect, likely stemming from the fact that the young adult bilinguals were all heritage speakers. The majority of them grew up speaking Spanish in the home until they entered school, and they are now either balanced or English-dominant, though they continue to speak Spanish almost exclusively in the home to parents and other relatives. So why would the older adult bilinguals, who are also high proficiency bilinguals, prefer to use English more in the home? One reason could be

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[4] In general, past research has suggested that findings among bilinguals who speak different languages are fairly consistent, and it is not the language per se that is influencing performance, but the cognitive control required to manage both languages in one brain (Bialystok, 2017).

because they are an older version of the young adult bilinguals. Though these older adults might have spoken Spanish in the home when they were younger (and this is likely the case since about two-thirds reported that Spanish was their first language), eventually these participants were no longer living with or seeing those parents or relatives, some of whom were likely Spanish monolinguals, on a regular basis. Instead, they might have been conversing in English in the workplace, with friends, and with spouses, which gave way to greater English use in the home over time. Regardless of the reason, it is important to consider whether this difference might have influenced cognitive performance in the two groups of bilinguals. Spanish use in the home was not a significant predictor of any behavioral or brain-related outcomes, so despite these differences in when and where the older and younger bilinguals reported using Spanish and English, it does not seem to have resulted in the two bilingual groups performing differently in any way.

In terms of the behavioral measures used to assess resistance to PI, both the directed forgetting and release from PI tasks would generally be considered long-term memory tasks. However, resistance to PI can also be assessed through working memory paradigms such as a recent probes task, in which letters or words that originally served as memory targets on prior trials become distractor items on current trials, leading to proactive interference (Jonides et al., 2000; Nee et al., 2007). Only the release from PI task used in the present study has been utilized in previous work to test resistance to PI abilities in bilinguals compared to monolinguals (Bialystok & Feng, 2009); my study is the first to utilize directed forgetting to assess bilingual versus monolingual differences in resistance to PI, and no studies have yet compared performance on a working memory-based resistance to PI task. Therefore, assessing resistance to PI via a working memory task seems like an important step forward in order to add to the small body of work that has examined resistance to PI in bilinguals to date.

Finally, one point that is still unclear from the present study, and quite truthfully the bilingualism field as a whole, is the rate at which language learning induces changes in brain and behavior. Much prior work in the bilingualism literature has suggested that learning a new language intensively over a short period of time stimulates structural changes in the brain (Hosoda et al., 2013; Martensson et al., 2012; Stein et al., 2012) and increased proficiency in the second language as evidenced through ERPs (White, Genesee, & Steinhauer, 2012), though there are few, if any, studies to date that have examined domain-general changes to behavior as a function of second language acquisition. An important follow-up to the work that has been done thus far would be to examine how short-term language training might lead to behavioral adaptations, in all aspects of cognition but particularly with regard to resistance to PI. While bilinguals and monolinguals did not show behavioral differences on the resistance to PI tasks tested herein, we know that when the bilinguals were first acquiring their second language, there were likely rapid brain changes that occurred as a result of this new learning (Lovden et al., 2013; Pliatsikas, 2019) and it is quite possible that these neural changes could have been paired with short-term enhancements in cognitive abilities. Since the bilinguals in my study were already proficient in both languages and had been actively using both for many years (in the case of the older adults, many decades), the neuroanatomical changes that typically result as a function of learning and experience could have already renormalized, and with those changes cognition may have stabilized as well.

Therefore, it seems that a critical step forward in the bilingualism field is to implement short-term second language training in order to determine how cognition changes as a result. This can also provide longitudinal insight (depending on the time course of training) into how cognitive abilities change as a function of learning another language, which is crucial to consider in an area that relies heavily on cross-sectional studies such as this one. I would expect that such behavioral changes might be present in both younger and older adults, since new learning appears to induce neural changes regardless of age (Lovden et al., 2013; Zatorre, Fields, & Johansen-Berg, 2012), and the acquisition of a second language in particular appears to support grey matter increases in the cortical regions that are not only important for language processing, but also resistance to PI (Pliatsikas, 2019). Thus, while it is likely that behavioral differences were not present in the current study due to the participants' lifelong experience with juggling multiple languages, it is still unclear how the early stages of the language learning process might alter resistance to PI performance.

Is the Brain Designed to be Multilingual?

Over the course of the past two decades, there has been a surge in the number of studies that have examined bilingualism and how bilinguals might differ from monolinguals, both behaviorally and with regard to brain structure. That said, it is interesting to think about how these studies have been framed over time. They are often designed in a way that perpetuates idea that the monolingual, both in terms of cognition and brain organization, is the norm – a gold standard that the bilingual must be held to in order to see if they measure up. However, it is abundantly clear that the majority of the world identifies as bi- or multilingual. Therefore, shouldn't bilingual cognition and brain structure be considered the model that monolinguals are compared to?

Indeed, there is no reason why the findings herein could not be framed in this way. For example, the finding of thicker cortex in several frontal regions among the monolinguals could be due to less cortical efficiency (e.g., not as much pruning of connections critical for language and inhibition) as a function of only relying on one language rather than managing two. Similarly, the brain might naturally be wired to create strong connections between right frontal grey and white matter to support the interplay between inhibition, language, and memory processes, but because only knowing one language does not require as many memory resources, links between memory-related tracts and cortical inhibition-related regions are not as strong. Moving forward, it is important to not just consider how bilinguals differ from monolinguals, but how the unique life experiences of these two groups of individuals distinctively shape the neural patterns that underlie successful cognitive performance.

Conclusions

This study is the first of its kind to demonstrate both cognitive reserve and brain reserve in distinct neural indices (grey matter and white matter, respectively) within the same group of participants. Not only does lifelong bilingualism seem to preserve cognitive performance in the face of cortical atrophy, but bilingualism also appears to moderate the relationship between white matter integrity and cognitive performance. Indeed, callosal volume is larger for older bilinguals than monolinguals, and greater FA is associated with several indices of greater resistance to PI and greater cortical thickness in regions important for inhibition among the bilinguals. In addition, this research demonstrated that maintenance of the first language, as evidenced through indices such as self-rated understanding of Spanish and self-reported current use of Spanish in day-to-day contexts, is linked to better resistance to PI performance and greater integrity of various cortical regions that underlie resistance to PI abilities. Overall, it appears that a bilingual's continual practice with inhibiting one of their two languages supports domain-general inhibition of irrelevant memory traces, a skill that becomes increasingly important to maintain with age, and that being bilingual is providing neural and cognitive protection that supports important structural links between the brain regions underlying inhibition, memory, and language processes.

References

Abutalebi, J., Canini, M., Della Rosa, P. A., Green, D. W., & Weekes, B. S. (2015a). The neuroprotective effects of bilingualism upon the inferior parietal lobule: A structural neuroimaging study in aging Chinese bilinguals. *Journal of Neurolinguistics, 33*, 3-13. doi:10.1016/j.jneuroling.2014.09.008

Abutalebi, J., Canini, M., Della Rosa, P. A., Sheung, L. P., Green, D. W., & Weekes, B. S. (2014). Bilingualism protects anterior temporal lobe integrity in aging. *Neurobiology of Aging, 35,* 2126-2133. doi:10.1016/j.neurobiolaging.2014.03.010

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

Abutalebi, J., Guidi, L., Borsa, V., Canini, M., Della Rosa, P. A., Parris, B. A., & Weekes, B. S. (2015b). Bilingualism provides a neural reserve for aging populations. *Neuropsychologia*, *69*, 201-210. doi:10.1016/j.neuropsychologia.2015.01.040

Aleman-Gomez, Y., Janssen, J., Schnack, H., Balaban, E., Pina-Camacho, L., Alfaro-Almagro, F., …Desco, M. (2013). The human cerebral cortex flattens during adolescence. *The Journal of Neuroscience, 33*(38), 15004-15010. doi:10.1523/JNEUROSCI.1459-13.2013

Alladi, S., Bak, T. H., Duggirala, V., Surampudi, B., Shailaja, M., Shukla, A. K….Kaul, S. (2013). Bilingualism delays age at onset of dementia, independent of education and immigration status. *Neurology, 81*(22), 1938-1944. doi:10.1212/01.wnl.0000436620.33155.a4

Antoniou, M. (2019). The advantages of bilingualism debate. *Annual Review of Linguistics, 5,* 1-21. doi:10.1146/annurev-linguistics-011718-011820.

Aron, A. R., Robbins, T. W., & Poldrack, R. A. (2004). Inhibition and the right inferior frontal cortex. *Trends in Cognitive Science, 8,* 170-177. doi:10.1016/j.tics.2004.02.010

Aron, A. R., Robbins, T. W., & Poldrack, R. A. (2014). Inhibition and the right inferior frontal cortex: One decade on. *Trends in Cognitive Science, 18,* 177-185. doi:10.1016/j.tics.2013.12.003

Badre, D. & Wagner, A. D. (2005). Frontal lobe mechanisms that resolve proactive interference. *Cerebral Cortex, 15*(12), 2003-2012. doi:10.1093/cercor/bhi075

Balota, D. A., Dolan, P. O., & Duchek, J. M. (2000). Memory changes in healthy older adults. In E. Tulving & F.I.M. Craik (Eds.), *The Oxford Handbook of Memory* (pp. 395-409). New York, NY: Oxford University Press.

Basden, B. H. (1996). Directed forgetting: Further comparisons of the item and list methods. *Memory, 4*(6), 633-654. doi:10.1080/741941000

Beatty-Martinez, A. L., & Dussias, P. E. (2017). Bilingual experience shapes language processing: Evidence from codeswitching. *Journal of Memory and Language, 95,* 173-189. doi:10.1016/j.jml.2017.04.002

Bialystok, E. (2017). The bilingual adaptation: How minds accommodate experience. *Psychological Bulletin, 143*(3), 233-262. doi:10.1037/bul0000099

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

Bialystok, E., Craik, F. I. M., Klein, R., & Viswanathan, M. (2004). Bilingualism, aging, and cognitive control: Evidence from the Simon task. *Psychology and Aging, 19,* 290-303. doi:10.1037/0882-7974.19.2.290

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

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

Bialystok, E. & Luk, G. (2012). Receptive vocabulary differences in monolingual and bilingual adults. *Bilingualism: Language and Cognition, 15*(2), 397-401. doi:10.1017/S136672891100040X

Bice, K. & Kroll, J. (2015). Native language change during early stages of second language learning. *NeuroReport, 26*(16), 966-971. doi:10.1097/WNR.0000000000000453

Bissett, P. G., Nee, D. E., & Jonides, J. (2009). Dissociating interference-control processes between memory and response. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 35*(5), 1306-1316. doi:10.1037/a0016537

Bjork, R. A. (1972). Theoretical implications of directed forgetting. In A.W. Melton & E. Martin (Eds.), *Coding Processes in Human Memory*, (pp. 217–235). Washington, DC: Winston.

Burgaleta, M., Sanjuan, A., Ventura-Campos, N., Sebastian-Galles, N., & Avila, C. (2016). Bilingualism at the core of the brain: Structural differences between bilinguals and monolinguals revealed by subcortical shape analysis. *NeuroImage, 125,* 437-445. doi:10.1016/j.neuroimage.2015.09.073

Campbell, K. L., Grady, C. L., Ng, C., & Hasher, L. (2012). Age differences in the frontoparietal cognitive control network: Implications for distractibility. *Neuropsychologia, 50,* 2212-2223. doi:10.1016/j.neuropsychologia.2012.05.025

Campbell, K. L., Hasher, L., & Thomas, R. C. (2010). Hyper-binding: A unique age effect. *Psychological Science, 21,* 399-405. doi:10.1177/0956797609359910

Costa, A., Hernandez, M., Costa-Faidella, J., & Sebastian-Galles, N. (2009). On the bilingual advantage in conflict processing: Now you see it, now you don't. *Cognition, 113,* 135-149. doi:10.1016/j.cognition.2009.08.001

Costa, A., Hernandez, M., & Sebastian-Galles, N. (2008). Bilingualism aids conflict resolution: Evidence from the ANT task. *Cognition, 106,* 59-86. doi:10.1016/j.cognition.2006.12.013

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

Cummine, J. & Boliek, C. A. (2013). Understanding white matter integrity stability for bilinguals on language status and reading performance. *Brain Structure and Function, 218,* 595-601. doi:10.1007/s00429-012-0466-6

Dale, A. M., Fischl, B., & Sereno, M. I. (1999). Cortical surface-based analysis: I. Segmentation and surface reconstruction. *NeuroImage, 9,* 179-194. doi:10.1006./nimg.1998.0395

Davidson, P. S. R., & Glisky, E. L. (2002). Neuropsychological correlates of recollection and familiarity in normal aging. *Cognitive, Affective, & Behavioral Neuroscience*, *2*(2), 174-186.

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

DeLuca, V., Rothman, J., & Pliatsikas, C. (2019b). Linguistic immersion and structural effects on the bilingual brain: A longitudinal study. *Bilingualism: Language and Cognition, 22*(5), 1160-1175. doi:10.1017/S1366728918000883

Desikan, R. S., Segonne, F., Fischl, B., Quinn, B. T., Dickerson, B. T., Blacker, D.…Killiany, R. J. (2006). An automated labeling system for subdividing the human cerebral cortex on MRI scans into gyral based regions of interest. *NeuroImage, 31,* 968-980. doi:10.1016/j.neuroimage.2006.01.021

Dick, A. S., Garcia, N. L., Pruden, S. M., Thompson, W. K., Hawes, S. W., Sutherland, M. T.…Gonzalez, R. (2018). No bilingual advantage for executive function: Evidence from a large sample of children in the Adolescent Brain and Cognitive Development (ABCD) Study. *PsyArXiv.* doi:10.31234/osf.io/gjh95

Duncan, H. D., Nikelski, J., Pilon, R., Steffener, J., Chertkow, H., & Phillips, N. A. (2018). Structural brain differences between monolingual and multilingual patients with mild cognitive impairment and Alzheimer disease: Evidence for cognitive reserve. *Neuropsychologia, 109,* 270-282. doi:10.1016/j.neuropsychologia.2017.12.036

Fabri, M., Pierpaoli, C., Barbaresi, P., & Polonara, G. (2014). Functional topography of the corpus callosum investigated by DTI And fMRI. *World Journal of Radiology, 6*(12), 895-906. doi:10.4329/wjr.v6.i12.895

Felton, A., Vazquez, D., Ramos-Nunez, A. I., Greene, A. I., Macbeth. A., Hernandez, A. E., & Chiarello, C. (2017). Bilingualism influences structural indices of interhemispheric organization. *Journal of Neurolinguistics, 42,* 1-11. doi:10.1016/j.jneuroling.2016.10.004

Fischl, B., Sereno, M. I., & Dale, A. M. (1999). Cortical surface-based analysis II: Inflation, flattening, and a surface-based coordinate system. *NeuroImage, 9,* 195-207.

Fischl, B., Sereno, M. I., Tootell, R. B., & Dale, A. M. (1999). High-resolution intersubject averaging and a coordinate system for the cortical surface. *Human Brain Mapping, 8,* 272-284.

Friedman, N. P. (2016). Research on individual differences in executive functions: Implications for the bilingual advantage hypothesis. *Linguistic Approaches to Bilingualism, 6,* 535-548. doi:10.1075/lab.15041.fri

Friedman, N. P., & Miyake, A. (2004). The relations among inhibition and interference control functions: A latent-variable analysis. *Journal of Experimental Psychology: General, 133*(1), 101-135. doi:10.1037/0096-3445.133.1.101

Friesen, D. C., Luo, L., Luk, G., & Bialystok, E. (2015). Proficiency and control in verbal fluency performance across the lifespan for monolinguals and bilinguals. *Language, Cognition, and Neuroscience, 30*(3), 238-250. doi:10.1080/23273798.2014.918630

Gold, B. T., Johnson, N. F., & Powell, D. K. (2013). Lifelong bilingualism contributes to cognitive reserve against white matter integrity declines in aging. *Neuropsychologia, 51,* 2841-2846. doi:10.1016/j.neuropsychologia.2013.09.037

Green, D. W., and Abutalebi, J. (2013). Language control in bilinguals: The adaptive control hypothesis, *Journal of Cognitive Psychology, 25*(5), 515-530. doi:10.1080/20445911.2013.796377

Groot, C., van Loenhoud, A. C., Barkhof, F., van Berckel, B. N. M., Koene, T., Teunissen, C. C., …Ossenkoppele, R. (2018). Differential effects of cognitive reserve and brain reserve on cognition in Alzheimer disease. *Neurology, 90, 149-156.* doi:10.1212/WNL.0000000000004802

Grosjean, F. (1998). Studying bilinguals: Methodological and conceptual issues. *Bilingualism: Language and Cognition*, *1*(2), 131-149. doi:10.1017/S136672899800025X

Grundy, J. G., Anderson, J. A. B., & Bialystok, E. (2017). Neural correlates of cognitive processing in monolinguals and bilinguals. *Annals of the New York Academy of Sciences, 1396,* 183-201. doi:10.1111/nyas.13333

Hamalainen, S., Sairanen, V., Leminen, A., & Lehtonen, M. (2017). Bilingualism modulates the white matter structure of language pathways. *NeuroImage, 152,* 249-257. doi:10.1016/j.neuroimage.2017.02.081

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

Hasher, L., Zacks, R. T., & May, C. P. (1999). Inhibitory control, circadian arousal, and age. In D. Gopher & A. Koriat (Eds.), *Attention and performance. Attention and performance XVII: Cognitive regulation of performance: Interaction of theory and application* (pp. 653-675). Cambridge, MA: The MIT Press.

Hedden, T., & Gabrieli, J. D. E. (2004). Insights into the aging mind: A view from cognitive neuroscience. *Nature Reviews Neuroscience*, *5*, 87-96. doi:10.1038/nrn1323

Heim, S., Stumme, J., Bittner, N., Jockwitz, C., Amunts, K., & Caspers, S. (2019). Bilingualism and "brain reserve': A matter of age. *Neurobiology of Aging, 81,* 157-165. doi:10.1016/jneurobiolaging.2019.05.021

Hilchey, M. D., & Klein, R. M. (2011). Are there bilingual advantages on nonlinguistic interference tasks? Implications for the plasticity of executive control processes. *Psychonomic Bulletin & Review*, *18*(4), 625-658. doi:10.3758/s13423-011-0116-7

Hogge, M., Adam, S., & Collette, F. (2008). Directed forgetting and aging: The role of retrieval processes, processing speed, and proactive interference. *Aging, Neuropsychology, and Cognition*, *15*(4), 471-491. doi:10.1080/13825580701878065

Hogstrom, L. J., Westlye, L. T., Walhovd, K. B., & Fjell, A. M. (2013). The structure of the cerebral cortex across adult life: Age-related patterns of surface area, thickness, and gyrification. *Cerebral Cortex, 23,* 2521-2530. doi:10.1093/cercor/bhs231

Hosoda, C., Tanaka, K., Nariai, T., Honda, M., & Hanakawa, T. (2013). Dynamic neural network reorganization associated with second language vocabulary acquisition: A multimodal imaging study. *Journal of Neuroscience, 21,* 13663-13672. doi:10.1523/JNEUROSCI.0410-13.2013

Hua, K., Zhang, J., Wakana, S., Jiang, H., Li, X., Reich, D. S., …Mori, S. (2008). Tract probability maps in stereotaxic spaces: Analyses of white matter anatomy and tract-specific quantification. *NeuroImage, 39,* 336-347. doi: 10.1016/j.neuroimage.2007.07.053

Jellison, B. J., Field, A. S., Medow, J., Lazar, M., Salamat, M. S., & Alexander, A. L. (2004). Diffusion tensor imaging of cerebral white matter: A pictorial review of physics, fiber tract anatomy, and tumor imaging patterns. *American Journal of Neuroradiology, 25,* 356-369.

Jenkinson, M., Beckmann, C. F., Behrens, T. E. J., Woolrich, M. W., & Smith, S. M. (2012). FSL. *NeuroImage*, *62*(2), 782-790. doi:10.1016/j.neuroimage.2011.09.015

Jonides, J., Marshuetz, C., Smith, E. E., & Reuter-Lorenz, P. A. (2000). Age differences in behavior and PET activation reveal differences in interference resolution in verbal working memory. *Journal of Cognitive Neuroscience, 12,* 188-196. doi:10.1162/089892900561823

Jonides, J. & Nee, D. E. (2006). Brain mechanisms of proactive interference in working memory. *Neuroscience, 139,* 181-193. doi:10.1016/j.neuroscience.2005.06.042

Jonides, J., Smith, E. E., Marshuetz, C., Koeppe, R. A., & Reuter-Lorenz, P. A. (1998). Inhibition in verbal working memory revealed by brain activation. *PNAS, 95,* 8410-8413.

Kane, M. J., & Engle, R. W. (2000). Working-memory capacity, proactive interference, and divided attention: Limits on long-term memory retrieval. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 26*(2), 336-358. doi:10.1037/0278-7393.26.2.336

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

Kochunov, P., Glahn, D. C., Lancaster, J., Thompson, P. M., Kochunov, V., Rogers, B., …Williamson, D. E. (2011). Fractional anisotropy of cerebral white matter and thickness of cortical gray matter across the lifespan. *NeuroImage, 58,* 41-49. doi:10.1016/j.neuroimage.2011.05.050

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

Kroll, J. F., & Bialystok, E. (2013). Understanding the consequences of bilingualism for language processing and cognition. *Journal of Cognitive Psychology, 25*, 497-514. doi:10.1080/20445911.2013.799170

Kroll, J. F., Dussias, P. E., Bice, K., & Perrotti, L. (2015). Bilingualism, mind, and brain. *Annual Review of Linguistics, 1,* 377-394. doi:10.1146/annurev-linguist-030514-124937

Kuperberg, G. R., Broome, M. R., McGuire, P. K., David, A. S., Eddy, M., Ozawa, F….Fischl, B. (2003). Regionally localized thinning of the cerebral cortex in schizophrenia. *Archives of General Psychiatry, 60,* 878-888. doi:10.1001/archpsyc.60.9.878

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

Li, P., Zhang, F., Tsai, E., & Puls, B. (2014). Language history questionnaire (LHQ 2.0): A new dynamic web-based research tool. *Bilingualism: Language and Cognition, 17*(3), 673-680. doi:10.1017/S1366728913000606

Lovden, M., Wenger, E., Martensson, J., Lindenberger, U., & Backman, L. (2013). Structural brain plasticity in adult learning and development. *Neuroscience and Biobehavioral Reviews, 37,* 2296-2310. doi:10.1016/j.neubiorev.2013.02.014

Luk, G., Bialystok, E., Craik, F. I. M., & Grady, C. L. (2011a). Lifelong bilingualism maintains white matter integrity in older adults. *The Journal of Neuroscience, 31,* 16808-16813. doi:10.1523/JNEUROSCI.4563-11.2011

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

Lustig, C., Hasher, L., & Zacks, R. T. (2007). Inhibitory deficit theory: Recent developments in a "new view". In D. S. Gorfein & C. M. MacLeod (Eds.), *The Place of Inhibition in Cognition* (pp. 145-162). Washington, DC: American Psychological Association.

MacLeod, C. M. (1999). The item and list methods of directed forgetting: Test differences and the role of demand characteristics. *Psychonomic Bulletin & Review, 6*(1), 123-129. doi:10.3758/bf03210819.

Madden, D. J., Bennett, I. J., Burzynska, A., Potter, G. G., Chen, N-K., & Song, A. W. (2012). Diffusion tensor imaging of cerebral white matter integrity in cognitive aging. *Biochimica et Biophysica Acta, 1822,* 386-400. doi:10.1016/j.bbadis.2011.08.003

Mamiya, P. C., Richards, T. L., & Kuhl, P. K. (2018). Right forceps minor and anterior thalamic radiation predict executive function skills in young bilingual adults. *Frontiers in Psychology, 9,* 1-10. doi:10.3389/fpsyg.2018.00118

Martin-Rhee, M., & Bialystok, E. (2008). The development of two types of inhibitory control in monolingual and bilingual children. *Bilingualism: Language and Cognition, 11,* 81-93. doi:10.1017/S1366728907003227

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

Marton, K., Goral, M., Campanelli, L., Yoon, J., & Obler, L. K. (2017). Executive control mechanisms in bilingualism: Beyond speed of processing. *Bilingualism: Language and Cognition*, *20*(3), 613-631. doi:10.1017/S1366728915000930

Mechelli, A., Crinion, J. T., Noppeney, U., O'Doherty, J., Ashburner, J., Frackowiak, R. S., & Price, C. J. (2004). Structural plasticity in the bilingual brain: Proficiency in a second language and age at acquisition affect grey-matter density. *Nature, 431,* 757.

Meschyan, G. & Hernandez, A. E. (2006). Impact of language proficiency and orthographic transparency on bilingual word reading: An fMRI investigation. *NeuroImage, 29,* 1135-1140. doi:10.1016/j.neuroimage.2005.08.055

Mohades, S. G., Struys, E., Van Schuerbeek, P., Mondt, K., Van De Craen, P., & Luypaert, R. (2012). DTI reveals structural differences in white matter tracts between bilingual and monolingual children. *Brain Research, 1435,* 72-80. doi:10.1016/j.brainres.2011.12.005

Mori, S., Wakana, S., Nagae-Poetscher, L. M., & Van Zijl, P. C. M. (2005). *MRI Atlas of Human White Matter.* Amsterdam, The Netherlands: Elsevier.

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

Nee, D. E., Jonides, J., & Berman, M. G. (2007). Neural mechanisms of proactive interference resolution. *NeuroImage, 38,* 740-751. doi:10.1016/j.neuroimage.2007.07.066

Nelson, J. K., Reuter-Lorenz, P. A., Persson, J., Sylvester, C-Y. C., & Jonides, J. (2009). Mapping interference resolution across task domains: A shared control process in left inferior frontal gyrus. *Brain Research, 1256,* 92-100. doi:10.1016/j.brainres.2008.12.001

Nelson, J. K., Reuter-Lorenz, P. A., Sylvester, C-Y. C., Jonides, J., & Smith, E. E. (2003). Dissociable neural mechanisms underlying response-based and familiarity-based conflict in working memory. *PNAS, 100,* 11171-11175. doi:10.1073/pnas.13341251

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*, *9*, 97-113. doi:10.1016/0028-3932(71)90067-4

Olulade, O. A., Jamal, N. I., Koo, D. S., Perfetti, C. A., LaSasso, C., & Eden, G. F. (2016). Neuroanatomical evidence in support of the bilingual advantage theory. *Cerebral Cortex, 26,* 3196-3204. doi:10.1093/cercor/bhv152

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

Papageorgiou, A., Bright, P., Tomas, E. P., & Filippi, R. (2019). Evidence against a cognitive advantage in the older bilingual population. *Quarterly Journal of Experimental Psychology, 72*(6), 1354-1363. doi:10.1177/1747021818796475

Pareek, V., Rallabandi, V. P. S., & Roy, P. K. (2018). A correlational study between microstructural white matter properties and macrostructural gray matter volume across normal ageing: Conjoint DTI and VBM analysis. *Magnetic Resonance Insights, 11,* 1-13. doi:10.1177/1178623X18799926

Pettigrew, C., & Martin, R. C. (2014). Cognitive declines in healthy aging: Evidence from multiple aspects of interference resolution. *Psychology and Aging, 29*(2), 187-204. doi:10.1037/a0036085

Pliatsikas, C. (2019). Understanding structural plasticity in the bilingual brain: The Dynamic Restructuring Model. *Bilingualism: Language and Cognition,* 1-13. doi:10.1017/S1366728919000130

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

Pliatsikas, C., Moschopoulou, E., & Saddy, J. D. (2015). The effects of bilingualism on the white matter structure of the brain. *PNAS, 112,* 1334-1337. doi:10.1073/pnas.1414183112

Rodriguez, S. M., Archila-Suerte, P., Vaughn, K. A., Chiarello, C., & Hernandez, A. E. (2018). Anterior insular thickness predicts speech sound learning ability in bilinguals. *NeuroImage, 165,* 278-284. doi:10.1016/j.neuroimage.2017.10.038

Rosas, H. D., Liu, A. K., Hersch, S., Glessner, M., Ferrante, R. J., Salat, D. H.,…Fischl, B. (2002). Regional and progressive thinning of the cortical ribbon in Huntington's disease. *Neurology, 58,* 695-701. doi:10.1212/WNL.58.5.695

Sakai, K. L. (2005). Language acquisition and brain development. *Science, 310,* 815-819. doi:10.1126/science.1113530

Salat, D. H., Buckner, R. L., Snyder, A. Z., Greve, D. N., Desikan, R. S., Busa, E....Fischl, B. (2004). Thinning of the cerebral cortex in aging. *Cerebral Cortex, 14*, 721-730. doi:10.1093/cercor/bhh032

Schlegel, A. A., Rudelson, J. J., & Tse, P. U. (2012). White matter structure changes as adults learn a second language. *Journal of Cognitive Neuroscience, 24,* 1664-1670. doi:10.1162/jon_a_00240

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

Sego, S. A., Golding, J. M., & Gottlob, L. R. (2006). Directed forgetting in older adults using the item and list methods. *Aging, Neuropsychology, and Cognition, 13,* 95-114. doi:10.1080/138255890968682

Shibata, H. & Naito, J. (2005). Organization of anterior cingulate and frontal cortical projections to the anterior and laterodorsal thalamic nuclei in the rat. *Brain Research, 1059,* 93-103. doi:10.1016/j.brainres.2005.08.025

Singh, N. C., Rajan, A., Malagi, A., Ramanujan, K., Canini, M., Della Rosa, P. A. …Abutalebi, J. (2017). Microstructural anatomical differences between bilinguals and monolinguals. *Bilingualism: Language and Cognition,* 1-14. doi:10.1017/S1366728917000438

Stein, M., Federspiel, A., Koenig, T., Wirth, M., Werner, S., Wiest, R., …Dierks, T. (2012). Structural plasticity in the language system relates to increased second language proficiency. *Cortex, 48,* 458-465. doi:10.1016/j.cortex.2010.10.007

Stern, Y. (2009). Cognitive reserve. *Neuropsychologia, 47,* 2015-2028. doi:10.1016/j.neruopsychologia.2009.03.004

Storsve, A. B., Fjell, A. M., Yendiki, A., & Walhovd, K. B. (2016). Longitudinal changes in white matter tract integrity across the adult lifespan and its relation to cortical thinning. *PLoS ONE, 11*(6), e0156770. doi:10.1371/journal.pone.0156770

Sumowski, J. F., Rocca, M. A., Leavitt, V. M., Dackovic, J., Mesaros, S., Drulovic, J.,…Filippi, M. (2014). Brain reserve and cognitive reserve protect against cognitive decline over 4.5 years in MS. *Neurology, 82,* 1776-1783. doi:10.1212/WNL.0000000000000433

Titz, C., & Verhaeghen, P. (2010). Aging and directed forgetting in episodic memory: A meta-analysis. *Psychology and Aging, 25*, 405-411. doi:10.1037/a0017225

Valian, V. (2015). Bilingualism and cognition. *Bilingualism: Language and Cognition, 18,* 3-24. doi:10.1017/S1366728914000522

Von Bastian, C. C., Souza, A. S., & Gade, M. (2016). No evidence for bilingual cognitive advantages: A test of four hypotheses. *Journal of Experimental Psychology: General, 145*, 246-258. doi:10.1037/xge0000120

Wang, L., Goldstein, F. C., Veledar, E., Levey, A. I., Lah, J. J., Meltzer, C. C., …Mao, H. (2009). Alterations in cortical thickness and white matter integrity in mild cognitive impairment measured by whole-brain cortical thickness mapping and diffusion tensor imaging. *American Journal of Neuroradiology, 30,* 893-899. doi:10.3174/ajnr.A1484

Weeks, J. C., & Hasher, L. (2018). Older adults encode more, not less: Evidence for age-related attentional broadening. *Aging, Neuropsychology, and Cognition*, *24*, 1-12. doi:10.1080/13825585.2017.1353678

White, E. J., Genesee, F., & Steinhauer, K. (2012). Brain responses before and after intensive second language learning: proficiency based changes and first language background effects in adult learners. *PLoS ONE, 7*(12), e52318. doi:10.1271/journal.pone.0052318

Wickens, D. D. (1970). Encoding categories of words: An empirical approach to meaning. *Psychological Review, 77*(1), 1-15. doi:10.1037/h0028569

Wickens, D. D., Born, D. G., & Allen, C. K. (1963). Proactive inhibition and item similarity in short-term memory. *Journal of Verbal Learning and Verbal Behavior, 2,* 440-445. doi:10.1016/S0022-5371(63)800456

Woodward, A. E., Park, D. C., & Seebohm, K. (1974). Directed forgetting as a function of explicit within-list cuing and implicit postlist cuing. *Journal of Experimental Psychology, 102*(6), 1001-1006. doi:10.1037/h0036387

Wu, M., Lu, L. H., Lowes, A., Yang, S., Passarotti, A. M., Zhou, X. J., & Pavuluri, M. N. (2014). Development of superficial white matter and its structural interplay with cortical gray matter in children and adolescents. *Human Brain Mapping, 35,* 2806-2816. doi:10.1002/hbm.22368

Zacks, R. T., Radvansky, G., Hasher, L. (1996). Studies of directed forgetting in older adults. *Journal of Experimental Psychology: Learning, Memory, & Cognition, 22*(1), 143-156. doi:10.1037/0278-7393.22.1.143

Zatorre, R. J., Fields, R. D., & Johansen-Berg, H. (2012). Plasticity in gray and white: Neuroimaging changes in brain structure during learning. *Nature Neuroscience, 15*(4), 528-536. doi:10.1038/nn.3045

Zhang, J. X., Leung, H-C., & Johnson, M. K. (2003). Frontal activations associated with accessing and evaluating information in working memory: An fMRI study. *NeuroImage, 20,* 1531-1539. doi:10.1016/j.neuroimage.2003.07.016