Evidence for cognitive and brain reserve supporting executive control of memory in lifelong bilinguals

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ABSTRACT

Recent bilingualism research attempts to understand whether continually controlling multiple languages provides domain-general benefits to other aspects of cognition. Yet little attention has been given to whether this extends to resistance to proactive interference (PI), which involves the filtering of irrelevant memory traces in order to focus attention on relevant to-be-remembered information. The present study sought to determine whether bilingualism provides benefits to resistance to PI performance and brain structure in regions supporting executive control of memory. Eighty-two younger and older adult participants, half English monolinguals and half highly proficient Spanish-English bilinguals, completed directed forgetting and release from PI tasks and underwent an MRI scan that measured cortical volume, thickness, and white matter integrity. While behavioral performance between bilinguals and monolinguals did not differ, bilinguals displayed thinner cortex in brain regions related to resistance to PI, providing evidence for cognitive reserve, and showed positive relationships between white matter integrity and resistance to PI performance, indicative of brain reserve. This study is the first to demonstrate cognitive reserve and brain reserve in different brain structure indices within the same healthy participants and suggests that bilingualism supports important structural relationships between regions necessary for executive control of memory.

1. Introduction

In the aging literature, two hypotheses have been proposed to explain how certain individuals are able to maintain intact cognition as they grow older. The first is brain reserve, which states that cognition will remain stable provided that the brain’s structural integrity is also preserved and does not decline past a fixed threshold (Stern, 2009). The second is cognitive reserve, which suggests that certain life experiences may preserve cognition despite brain atrophy (Stern, 2009). These life experiences can include higher levels of education, a more intellectually demanding occupation, or knowing and regularly using two languages. While aging eventually affects nearly all aspects of cognition, memory is one of the first cognitive processes to decline with increasing age (Hedden and Gabrieli, 2004). To promote maintenance of memory abilities, training skills that require executive control of memory is important since successful remembering is contingent upon selective, intentional rehearsal of relevant information (Bjork, 1972). Bilinguals may inadvertently receive such training as a function of managing two language systems, and recurrent practice of these skills might also serve as a possible reserve mechanism, helping bilinguals maintain cognitive abilities into old age. Thus, the primary aims of this study were to understand how bilingualism might affect certain aspects of memory performance, whether these potential benefits were present in both younger and older adulthood, and how the neural correlates of executive control of memory might differ between bilinguals and monolinguals, possibly supporting the notions of brain reserve or cognitive reserve as a consequence of lifelong bilingualism.

1.1. Resistance to proactive interference, aging, and bilingualism

In a seminal paper, Friedman and Miyake (2004) identified three types of interference control: prepotent response inhibition (suppressing automatic responses, e.g., a stop-signal or Stroop task), resistance to distractor interference (ignoring irrelevant perceptual distractions in the
external environment, e.g., a flanker task), and resistance to proactive interference (ignoring previously learned, but now irrelevant, information to achieve task goals, e.g., a Brown-Peterson variant used by Kane and Engle, 2000). In considering how these types of interference control differ, resistance to proactive interference (henceforth abbreviated as PI) manages interference resulting from irrelevant information being held in memory, whereas the interference in prepotent response/distraction inhibition stems from lower-level perceptual processing of a stimulus array, and further deciding whether or not to initiate an action in response to the stimulus (Pettigrew and Martin, 2014).

Resistance to PI is commonly measured via tasks such as release from PI and directed forgetting. During release from PI, interference builds up as a function of attempting to remember lists of similar items, but release from interference and a subsequent increase in memory performance occurs once dissimilar items are introduced (Wickens et al., 1965). Changes in semantic content produce some of the largest release from PI effects (Wickens, 1970). In directed forgetting, 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 successfully inhibiting “to-be-forgotten” stimuli. In both cases, executive control is required for participants to ignore irrelevant memory traces in favor of newer, more pertinent information.

With increased age, poorer performance on resistance to PI tasks becomes more prevalent (Hasher and Zacks, 1988; Lustig et al., 2001; May et al., 1999; Pettigrew and Martin, 2014). This effect is thought to be due to a decline in inhibitory processes (Hasher and Zacks, 1988) as well as an “attentional broadening” that results from not being able to filter relevant information from distracting information (Weeks and Hasher, 2018). Pettigrew and Martin (2014) found that older adults performed worse on a release from PI task compared to young adults. Further, older adults often remember more “to-be-forgotten” items during directed forgetting tasks than younger adults, indicating that they struggle to filter previously experienced, but now irrelevant information (Hogge et al., 2008; Weeks and Hasher, 2018; Zacks et al., 1996). A recent meta-analysis similarly concluded that the directed forgetting effect appears to be stronger in younger than in older adults, indicating that older adults are worse at forgetting irrelevant material (Titz and Verhaeghen, 2010). It appears that both release from PI and directed forgetting tasks are able to capture the attentional broadening mechanisms that older adults may undergo, leading to poorer executive control of memory with increasing age.

Given the behavioral evidence, it likely follows that the decline in resistance to PI performance is linked to the decline of important neural mechanisms as a function of increasing age. Resistance to PI tasks activate the inferior frontal gyrus (IFG; Badre and Wagner, 2005; Jonides et al., 1998), a region implicated in language processing (Sakai, 2005) and inhibition (Aron et al., 2004, 2014). Older adults demonstrate significantly less activity in the left IFG during resistance to PI tasks compared to younger adults, and lower activity is 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).

In addition to activation in the left IFG for PI resolution, greater activity has also been observed in bilateral middle frontal gyrus (MFG) and anterior cingulate cortex (ACC; Nelson et al., 2003; Zhang et al., 2003). Jonides and Nee (2006) concluded that resolving instances of PI involves a network of prefrontal regions typically implicated in cognitive control processes, a claim supported by strong functional connectivity between the IFG and ACC during resistance to PI (Nee et al., 2007). In addition, activation of the IFG and the MFG has been found for conditions evoking greater PI on a recent probes task and a verb generation task (Nelson et al., 2009). In sum, research into the neural mechanisms of PI resolution has identified the IFG, MFG, and ACC as the most active regions during resistance to PI.

While the prior studies focused on neural activity during PI tasks, they did not examine structural changes in these brain regions. However, other cross-sectional data have indicated that the structure and integrity of the IFG, MFG, and ACC begin declining in young adulthood and continue to deteriorate throughout the lifespan (Hedden and Gabrieli, 2004).

The IFG, MFG, and ACC are also noteworthy in that they have not only been implicated in resistance to PI tasks, but in the bilingualism literature as well (Li et al., 2014), as regions that bilinguals invoke to mediate conflict and interference between their two languages. Structural differences between monolinguals and bilinguals have been repeatedly found in cognitive control regions, with bilinguals typically exhibiting greater grey matter volume (Abutalebi et al., 2012, 2015a, 2015b; Mechelli et al., 2004; Oulade et al., 2016), cortical thickness (Felton et al., 2017; Klein et al., 2014; Olsen et al., 2015), and white matter integrity (Lu et al., 2011; Mohades et al., 2012; Platsikas et al., 2015; Schlegel et al., 2012). It is unclear though whether structural integrity of the IFG, MFG, and ACC is associated with behavioral differences in executive control of memory. Thus, determining whether neural distinctions between bilinguals and monolinguals are related to performance differences on resistance to PI tasks between the two groups is an important step forward in understanding the effect of bilingual experience on brain and behavior.

Up to this point, only one study has examined executive control of memory via a resistance to PI task in bilinguals versus monolinguals (Bialystok and Feng, 2009). In this study, early bilingual and monolingual children and young adults performed a release from PI task. Participants were sequentially presented with three lists all composed of words from the same category; after the presentation of each list, they recalled as many words as possible from that particular list. While at first it appeared that the pattern of PI buildup and release did not differ between the monolingual and bilingual children, when differences in vocabulary were accounted for, the bilinguals demonstrated a recall advantage over monolinguals across all four lists (Bialystok and Feng, 2009). This study provides preliminary evidence suggesting that advantages in resistance to PI might exist among bilinguals who acquired a second language early in life. If bilinguals possess superior domain-general interference control mechanisms as a function of managing interference between one’s two languages, then these benefits might carry over to certain aspects of memory processing such as resistance to PI.

1.2. The bilingual brain and reserve

Several studies support the notion of larger, more intact brain structures among older adult bilinguals compared to monolinguals. Greater grey matter volume (GMV) has been found in the left temporal pole (Abutalebi et al., 2014) and the inferior parietal lobe (IPL; Abutalebi et al., 2015a) among bilingual older adults. In these cross-sectional studies, age effects were observed for monolinguals, indicating more atrophy of GMV with older age, but this pattern was not observed among the bilinguals, implying that bilinguals maintain cortical integrity into old age. This is consistent with the brain reserve hypothesis.

Other work suggests that although both monolinguals and bilinguals experience age-related volume decreases in the prefrontal cortex, poorer cognitive performance is associated with this decline only for the monolinguals (Abutalebi et al., 2015b). Interestingly, the bilinguals in this study also showed greater GMV in the ACC than monolinguals, indicating brain reserve. These findings imply that certain brain regions decline more slowly for bilinguals than monolinguals, and while structural loss may be inevitable in regions such as frontal cortex (Hedden and Gabrieli, 2004), cognition seems to be preserved as a function of using two languages throughout the lifespan.

While studies that have compared grey matter in bilingual and monolingual older adults typically find evidence for brain reserve, the white matter evidence is more mixed. A diffusion tensor imaging (DTI) examination of white matter integrity in lifelong bilinguals showed
significantly greater fractional anisotropy (FA; a measure of water diffusivity with values closer to 1 indicating greater tract integrity) in the corpus callosum compared to monolinguals, and this increased integrity extended bilaterally to the superior longitudinal fasciculus (SLF), the right inferior fronto-occipital fasciculus (IFOF), and right uncinate fasciculus (UF; Luk et al., 2011), consistent with the brain reserve hypothesis. Additionally, monolingual older adults had significantly higher RD (radial diffusivity; indicates poorer white matter integrity) in the corpus callosum than the bilinguals (Luk et al., 2011). However, a different study by Gold et al. (2013) found their bilingual sample had lower FA in the IFOF, inferior longitudinal fasciculus (ILF), corpus callosum, and fornix than the monolinguals, as well as higher RD in the IFOF and corpus callosum. An explanation for these divergent findings evokes the cognitive reserve hypothesis. The bilinguals and monolinguals in Gold et al.’s study were matched for several factors typically used as proxies for cognitive reserve, such as years of education and IQ. The findings by Gold et al. (2013) provide convincing evidence that being bilingual could lead to cognitive reserve, effectively showing that when older bilinguals are cognitively equivalent to monolinguals, their neural atrophy is more extreme.

Additional evidence for cognitive reserve comes from studies of Alzheimer’s progression. In general, bilinguals exhibit symptoms of dementia approximately 4–5 years later than monolinguals do (Alladi et al., 2013; Bialystok et al., 2007; Craik et al., 2010). However, some studies have examined cognitive reserve in bilinguals and monolinguals who are demonstrating symptoms of mild cognitive impairment (MCI) or Alzheimer’s disease. Lifelong bilinguals with Alzheimer’s showed greater brain atrophy in medial temporal regions compared to matched monolingual patients with Alzheimer’s (Schweizer et al., 2012).

Another recent examination compared cortical thickness and grey matter density of brain regions important for memory and cognitive control in lifelong multilinguals and monolinguals diagnosed with MCI or Alzheimer’s disease (Duncan et al., 2018). Both the MCI and Alzheimer’s multilinguals showed thicker cortex and increased grey matter density in the IFG and MFG compared to the matched monolinguals, providing evidence for brain reserve in the multilingual sample. While multilinguals with MCI and Alzheimer’s showed greater hippocampal density than the monolinguals, in other 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 multilinguals compared to the Alzheimer’s multilinguals. The hippocampal findings support brain reserve, but the differences in the other medial temporal regions are best explained by cognitive reserve. These results are important in that they demonstrate support for brain and cognitive reserve within the same group of individuals. Brain regions 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. However, regions involved in language and cognitive control processes do not seem to be affected by the same disease progression (Duncan et al., 2018). Instead, these regions remain more structurally intact in the multilingual group, demonstrating that the bilingual brain can exhibit plasticity in numerous ways. An important consideration is that these patients had experienced neurodegeneration, so it is unclear whether cognitive and brain reserve are observed at higher rates for multilinguals during the typical aging process.

Taken together, the findings suggest that structural differences between bilinguals and monolinguals in both grey and white matter are present throughout the adult lifespan. However, 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 exception known 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 co-occur and what their combined effects on behavior may be.

Additionally, the majority of these neuroimaging studies have not included cognitive tasks in their experiments, providing little means to assess how brain differences might relate to behavioral differences. Some studies do give participants neuropsychological tests, which may include an executive control task (e.g., the Stroop task; Luk et al., 2011), but these tasks are typically used to match groups rather than to explore individual differences in task performance. Bilingual brains are thought to differ in certain structural aspects from monolingual brains because bilinguals routinely employ greater levels of executive control to continually manage their two languages (Bialystok, 2017). However, from the present literature there is little evidence available to determine whether the structural differences seen in bilinguals (compared to monolinguals) have any behavioral consequences.

1.3. The present study

The aims of this research were threefold. The first goal was to investigate whether bilingualism was associated with enhanced executive control of information in memory. Little research has been published to date examining whether bilinguals show an advantage over monolinguals in resistance to PI. Our second goal was to investigate whether being bilingual aided in the preservation of memory abilities in aging. Older adults tend to perform more poorly on resistance to PI tasks compared to younger adults, but it is unclear whether bilingualism modulates this effect. Finally, we explored whether bilingual and monolingual brains differ, particularly in regions important for executive control and memory, and whether the relationship between brain structure and behavioral performance differed between the groups.

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 (Abutalebi et al., 2012, 2015b) have actually examined the relationship between brain structure and cognitive performance within the same participants. We examined both younger and older adult bilinguals and monolinguals; to our knowledge, no prior studies have compared all four of these groups within a single neuroimaging study.

To answer these questions, behavioral measures and multimodal structural neuroimaging were used. Participants completed two tasks that induce PI: a directed forgetting task and a release from PI task. Comparisons were made between younger and older adults as well as bilinguals and monolinguals within each age group. In addition, brain structure was compared between groups using surface-based measures of volume and thickness of the cortex, and DTI of underlying white matter tracts. In many instances, we chose to examine how the bilinguals as a whole, regardless of age, differed from the monolinguals. We suspected that behavior or brain organization might intrinsically differ between the two groups as a function of the bilinguals’ experience managing two language systems. We also compared cognitive performance of the older and younger adults within the bilingual group, to see how age might be interacting with any potential benefits of being bilingual. Studying how bilingualism may affect memory ability and associated brain structures in an aging population is a novel pursuit and will provide new insights into how lifelong bilingualism can impact both brain and behavior.

Predictions were rooted in the theoretical principles of brain reserve and cognitive reserve. The brain reserve hypothesis would predict worse performance overall on the resistance to PI tasks by older adults than the younger adults (e.g., Pettigrew and Martin, 2014), as well as an interaction such that older monolinguals are expected to perform more poorly than both older bilinguals and younger adults. Coupled with intact behavioral performance, we would expect the older bilinguals to show greater GMV and cortical thickness in cognitive control regions (ACC, IFG, MFG) compared to older monolinguals. These regions are important for executive function and resistance to PI (Jonides and Nee, 2006), and have been found to differ between bilinguals and monolinguals in past studies (Abutalebi et al., 2015b; Felton et al., 2017; Klein...
et al., 2014). In addition, white matter integrity in tracts underlying frontal and medial temporal memory regions (e.g., cingulum, SLF, UF) and tracts connecting the two hemispheres (e.g., the corpus callosum) should be greater in older bilinguals than older monolinguals (such as in Luk et al., 2011).

On the other hand, the cognitive reserve hypothesis would predict comparable behavioral performance on the resistance to PI tasks between the older adult groups (with both groups performing worse than the young adults), coupled with reduced structural integrity in the grey and white matter regions of interest specified previously, for the older bilinguals only. Cognitive reserve is defined as brain atrophy coupled with intact cognitive performance (Stern, 2009); if this pattern exists, we might conclude that lifelong bilingualism has afforded these older adults a cognitive mechanism by which to maintain behavioral performance, despite neural deterioration. Of course, the cognitive reserve hypothesis suggests that the groups being compared are matched on neuropsychological performance, as was done herein.

We would not expect any structural differences between the bilingual and monolingual young adults. This prediction is based on the Dynamic Restructuring Model (Platsikas, 2020), which suggests cortical grey matter changes are most prominent among bilinguals with late exposure to a second language and those who are still mastering their second language (e.g., Klein et al., 2014; Martensson et al., 2012). Since we expected that the young adult bilinguals in our Southern California sample would be either simultaneous or early sequential bilinguals with immersive language experience throughout their lives, we hypothesized cortical changes that may have occurred previously in the bilinguals had since renormalized (Platsikas, 2020). Additionally, we did not expect behavioral differences between monolingual and bilingual young adults, since they all should be performing at their cognitive peak (Bialystok, 2017).

In addition to the aforementioned group comparisons, correlational analyses were conducted to test several possible relationships between our variables of interest. Since directed forgetting and release from PI tasks are presumably both measures of resistance to PI but have not been used together in the same study, we assessed whether the outcome variables in each task were measuring the same construct. Additionally, we examined the relationship between resistance to PI performance and integrity measures of our grey and white matter regions of interest to assess whether variations in brain structure are associated with memory behavior.

2. Materials and methods

2.1. Participants

The present study included 103 individuals. Of these participants, 54 were young adults (17 male) aged 18–30 years ($M = 20.48$, $SD = 2.41$) and 49 were older adults (17 male) aged 55–85 years ($M = 68.86$, $SD = 7.49$). Younger adults were recruited from the UC Riverside student population. Older adults were recruited from UC Riverside’s lifespan database and the surrounding community. 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. We chose to specifically focus on Spanish-English bilinguals in the present study because in Riverside County, Spanish is the most prevalent non-English language, with 34.1% of residents using Spanish regularly in the home (U.S. Census Bureau, 2019). All participants were right-handed (Oldfield, 1971), had normal or corrected-to-normal vision, and no history of brain-related disease or injury. All participants were compensated ($10/hour for young adults, $15/hour for older adults), and older adults were also reimbursed for transportation costs.

2.1.1. Age matching

Only 50 young adults (25 bilingual) and 37 older adults (16 bilingual) completed the MRI scanning procedure and had useable MRI data in addition to the behavioral data. Further, in this sample the monolingual and bilingual older adults differed significantly in terms of age; monolinguals ($M = 72.38$, $SD = 6.33$) were older than bilinguals ($M = 66.75$, $SD = 7.24$), $t(35) = 2.52$, $p = .02$. 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 ($M = 20.32$, $SD = 2.06$) and 32 older adults ($M = 68.38$, $SD = 6.15$), used for all subsequent analyses. 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.

2.1.2. Assessing bilingual status

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’ language status was further evaluated at the time of testing via a language history questionnaire that asked the participants to report information about their language background and use.

2.2. Behavioral testing procedure

Participants completed two testing sessions at the UC Riverside campus. In the first session, participants completed a series of behavioral tasks and questionnaires on a computer, and in the second session, participants underwent a 30-min structural MRI scan and completed additional computer-based behavioral testing. The average time between the two testing sessions was 11–12 days ($M = 11.51$, range = 0–71 days). 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 behavioral tasks were presented via either E-Prime 2.0 or Matlab 2016b, and questionnaire data was collected through Qualtrics online survey software.

During the first testing session, the directed forgetting task was presented first, followed by several other tasks that tested a wide range of cognitive abilities (e.g., vocabulary measures, task switching, working memory), and testing ended with the release from PI task. Tasks were presented in the same order to each participant. Only the tasks relevant for the present research questions are described below, followed by imaging parameters for the MRI scan.

2.2.1. Screening

All participants underwent a thorough screening process to determine eligibility, either over the phone or in person. The screening asked about age, handedness, language 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). Potential participants who were screened in person completed the entire MoCA. If participants were determined to be eligible based on their answers to the screening questions and MoCA scores (at least 14 out of 20 for the partial MoCA or 21 out of 30 for the full MoCA), they were scheduled for testing. Those who completed the partial MoCA over the phone finished it in person at the beginning of their first session.
2.2.2. Directed forgetting

In this item-method directed forgetting task (Sego et al., 2006; Titz and Verhaeghen, 2010), participants were shown a list of 46 words between four and seven letters each, presented one at a time on the computer monitor. During the encoding phase, each trial began with the presentation of a fixation cross for 1 s, followed by a target word that appeared on the screen for 3 s. Participants were instructed to read the word out loud when it appeared. The word was then followed by a remember (“RRRR”) or forget (“FFFF”) cue which was also presented on the screen for 3 s. Participants were instructed to remember the words they were cued to remember and to forget the words they were cued to forget. Forty of the 46 words 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 other six words were always presented as the first and last three words, appearing in the same order with the same cues, to control for primacy and recency effects.

After encoding, participants were given 3 min to complete a 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. Afterward, they were asked to recall as many words from the encoding phase as they could remember by writing them down. They were told that they could recall and write down both “to-be-remembered” words and “to-be-forgotten” words, despite the instructions they were given at the beginning of the task.

2.2.3. Multilingual naming test

The Multilingual Naming Test (MINT; Gollan et al., 2012) is a picture naming task that has been normed in English and Spanish. During the task, pictures of objects were presented on the screen one at a time and remained until the participant made a verbal response, or a maximum of 5 s. Participants were instructed to say the name of each object, or if they did not know what the object was, to say, “I don’t know.” There were five practice trials and 68 experimental trials. The total score on the experimental trials was used as a measure of language proficiency and vocabulary knowledge, to control for effects of language ability on resistance to PI memory performance (for a similar method, see Bialystok and Feng, 2009). Bilinguals often demonstrate smaller vocabularies than monolinguals in their common language (Bialystok et al., 2010; Bialystok and Luk, 2012), which could influence performance on verbal tasks. Thus, controlling for vocabulary knowledge is important for identifying cognitive performance differences independent of the effects of vocabulary knowledge. Monolinguals completed the MINT in English, and bilinguals completed the MINT in one language (either Spanish or English) during Session 1 and in the other language during Session 2, after the MRI scan.

2.2.4. Release from PI

In this task, participants saw 10 words presented on a computer monitor one at a time for 3 s each. The words were all semantically related, belonging to the category of either “body parts” or “occupations.” Participants were instructed to read each word out loud as it appeared on the screen. After viewing the set of words, participants were instructed to count backwards by threes for 15 s, beginning with a randomly generated three-digit number. Participants were then given a blank sheet of paper and asked to recall as many words as they could from the list of words they had read earlier. They repeated the same sequence for the three remaining lists (encoding, backwards counting, and recall). Critically, the same semantic category was used 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 were given words from the category “body parts” for the first three lists and “occupations” for the fourth list, and the other half were given words from the category “occupations” for the first three lists and “body parts” for the fourth list.

2.3. MRI acquisition and processing pipeline

Each participant was scanned on a 3T Siemens Prisma at the UC Riverside Center for Advanced Neuroimaging. 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 mm³. All T1-weighted images were visually checked by a trained research assistant for artifacts such as missing brain tissue, wrapping, ringing, ghosting, susceptibility, radiofrequency inhomoogeneity and noise, and motion. FSLeyes was used for brain visualization. Any serious issues were confirmed by the study’s primary investigator. The imaging data for two older adults were excluded due to excessive motion; however, these participants were not part of the age-matched group of 32 older adult brains used in the present analyses.

2.3.1. Anatomical measurements

Cortical reconstruction and volumetric segmentation for all participants was performed using the FreeSurfer 6.1 analysis suite (Dale et al., 1999; Fischl et al., 1999a, 1999b), which is documented and freely available for download online (http://surfer.nmr.mgh.harvard.edu/). Briefly, processing included 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 identified 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, estimated total intracranial volume (eTIV), and parcellation volume values were automatically extracted for each hemisphere by FreeSurfer.

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 (ROI) 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 the “ACC” ROI, pars opercularis, pars orbitalis, and pars triangularis were combined to create the “IFG” ROI, and rostral and caudal MFG were combined to create the “MFG” ROI, for each hemisphere. The volumes of the parcellations were summed together to determine the total GMV for each 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. The archived conversation from the FreeSurfer listerv regarding the summing procedure, as well as the appropriate calculation, can be found at https://www.mail-archive.com/freesurfer@nmr.mgh.harvard.edu/msg16040.html. The bilateral precentral and postcentral gyri were included as control regions since no structural differences due to bilingualism were expected in these areas.
2.4. DTI acquisition and processing pipeline

One diffusion-weighted echo-planar imaging (EPI) sequence was acquired in the anterior-to-posterior direction with TR = 3500 ms, TE = 102 ms, FOV = 218 × 218 mm, 72 axial slices, and 1.7 mm³ spatial resolution. For the sequence, gradients (b = 1500 and 3000 s/mm²) were applied in 64 orthogonal directions, with six images having no diffusion weighting (b = 0). Afterward, a second sequence with the same parameters was used to acquire six b0 volumes in the posterior-to-anterior direction, for field inhomogeneity correction during preprocessing.

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. A diffusion tensor model was computed at each voxel. To process the data for the tract-based spatial statistics (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. 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. To create masks for the tracts of interest, we utilized the ICBM-DTI-81 White Matter Labels Atlas (Mori et al., 2005) and the JHU White Matter Tractography Atlas (Hua et al., 2008). Three masks were created for the corpus callosum (corresponding to the genu, body, and splenium), and also for bilateral cingulum, SLF, and UF. These regions were chosen based on a priori predictions mentioned previously.

Next, voxel-wise statistics on the skeletonized FA data were computed using the “randomise” 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 priori definition of a cluster-forming threshold. Skeletonized data for all participants were 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, for whole-brain FA as well as for individual tracts of interest.

2.5. Data preparation

Prior to analysis, the data was screened for outliers or other abnormal data points by the researchers; none were found. Most dependent variables of interest met the assumptions for normality and homoscedasticity. Only two variables were not normally distributed; the proportion of to-be-forgotten words retrieved (from directed forgetting) and the proportion of intrusion errors (from release from PI) were both positively skewed, since the majority of participants did not make any errors. Analyses of these two measures are included below with the other relevant findings but should be interpreted with caution.

3. Results

3.1. Sample characteristics

MoCA scores were comparable across all four groups (M = 26.77, SD = 2.10), with no significant differences between age groups, F < 1, or between 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. Participants chose their highest level of education from a ranked list of twelve possible options, ranging from “some elementary school” (1) to “Doctoral or advanced degree” (12). Younger adults reported a mean education level of 7.2, where 7 is equivalent to “some college.” Older adults reported a mean educational achievement of 8.9, where 9 is equivalent to “Associate’s degree.” The older adults had significantly more formal education than the younger adults, F(1, 78) = 22.62, p < .001; this is fairly typical in cross-sectional studies as the young adults are usually current college students that have not yet completed their education. Monolinguals and bilinguals did not differ with regard to education, F < 1, nor was there an interaction, F(1, 78) = 3.15, p = .08.

3.2. Language proficiency

3.2.1. Language history questionnaire

The participants’ linguistic characteristics are detailed in Table 1. The majority of the bilingual participants (78.0%) were early bilinguals, meaning they acquired both languages by age 3–4, on average. Spanish age of acquisition (AoA) did not differ between the younger and older bilinguals, t(39) = 1.60, p = .12. English was acquired significantly later for the younger bilinguals compared to the younger monolinguals, t(48) = 5.65, p < .001, and for the older bilinguals compared to the older monolinguals, t(30) = 2.69, p = .01. However, the AoA differences between the bilinguals and monolinguals appeared to have little bearing on their current language proficiency.

Participants were asked to self-report their current proficiency in English, and also in Spanish if they were bilingual. Proficiency was rated separately for speaking, reading, writing, and understanding, using a scale of 0–10 (0 = “None”, 10 = “Native-like”). 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 for English speaking: monolinguals (M = 9.63, SD = 0.80) reported better speaking ability in English than bilinguals (M = 9.24, SD = 1.02), F(1, 78) = 4.88, p = .03, though all group averages were above 9. When comparing within age groups, younger bilinguals and monolinguals did not differ in any aspect of their English proficiency, t < 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. When comparing the older and younger bilinguals on their Spanish proficiency, the two

<table>
<thead>
<tr>
<th>Table 1</th>
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<tbody>
<tr>
<td>Means and (SDs) for the self-reported language characteristics each group.</td>
</tr>
<tr>
<td></td>
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<tr>
<td></td>
</tr>
<tr>
<td>English AoA (years)</td>
</tr>
<tr>
<td>Speaking</td>
</tr>
<tr>
<td>Reading</td>
</tr>
<tr>
<td>Writing</td>
</tr>
<tr>
<td>Understanding</td>
</tr>
<tr>
<td>English Use (%)</td>
</tr>
<tr>
<td>Free Time</td>
</tr>
<tr>
<td>Spanish AoA (years)</td>
</tr>
<tr>
<td>Spanish Proficiency (0–10)</td>
</tr>
<tr>
<td>Reading</td>
</tr>
<tr>
<td>Writing</td>
</tr>
<tr>
<td>Understanding</td>
</tr>
<tr>
<td>Spanish Use (%)</td>
</tr>
<tr>
<td>Free Time</td>
</tr>
</tbody>
</table>

Note. Bolded scores indicate a significant difference (p < .05) between groups.
groups only differed in self-rated understanding, t(39) = 2.10, p = .04.

Regarding self-reported frequency of language use, the monolinguals almost exclusively used English while the bilinguals reported using a mix of English and Spanish (see Table 1). The younger bilinguals reported significantly greater use of Spanish in the home than the older bilinguals, (t(39) = 5.51, p < .001, and conversely, significantly less use of English in the home, t(39) = 5.23, p < .001. However, the younger and older bilinguals reported using English and Spanish with similar frequencies during their free time, p > .05. Self-reported use of language in the home is hard to compare between the two bilingual groups because it is unknown how the young adults are defining “home” – they could be referring to their dorm or apartment, or referring to their family home, which they might only visit occasionally. Therefore, the comparison of language use among the younger and older bilinguals in their free time is likely a more accurate comparison of language usage and further supports the notion that our bilingual samples are well-matched regarding their language abilities. The greater use of English compared to Spanish by the bilinguals during free time makes sense given the predominantly monolingual English contexts in which these participants were immersed in Southern California. Despite predominant English use, high self-reported and lab-based Spanish proficiency scores solidify the classification of these individuals as bilingual.

3.2.2. MINT

The four groups were compared on English MINT performance using a 2 (age group) x 2 (language group) ANOVA. The monolinguals (M = 62.8, SD = 2.9) had significantly higher scores than the bilinguals (M = 59.5, SD = 4.9), F(1, 78) = 14.69, p < .001, which is consistent with other work (e.g., Bialystok and Luk, 2012). However, there were no differences between younger and older adults, F(1, 78) = 3.17, p = .08, nor was there an interaction, F < 1. On the Spanish MINT, there was no difference between the younger (M = 43.3, SD = 9.8) and older (M = 45.3, SD = 13.2) adults, t < 1, so all the bilinguals were comparable in Spanish vocabulary knowledge. Still, the bilinguals named fewer pictures in Spanish (M = 44.1, SD = 11.1) compared to English (M = 59.5, SD = 4.9), t(40) = 7.92, p < .001.

3.3. Directed forgetting

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

Younger adults retrieved more to-be-remembered (TBR) words than the older adults (see Fig. 1A), F(1, 77) = 6.92, p = .01, but there were no significant differences between bilinguals and monolinguals, F < 1, and no interaction between age and language group, F < 1. English MINT performance 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, or language group, F(1, 77) = 1.24, p = .27, and no

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1 A reviewer pointed out that the young adult monolinguals had high variability in their “free time” English use, despite high mean usage of English, and wondered whether the monolingual and bilingual groups could be clearly distinguished in our sample. The larger standard deviation for this measure is being driven by five participants who reported that they did not use English exclusively during their free time. Two of these participants only reported knowing English, so it is unclear what other language, if any, they used when not speaking English. Since they reported using English 100% of the time in other contexts, these two cases may have resulted from an error in data entry. A third participant reported that their second language was Pig Latin (a made-up language game), which they used during 40% of their free time. The remaining two participants reported knowing Spanish to some extent, but were not very proficient (average proficiency = 45/10). Therefore, we remain confident in our classification of these participants as functional monolinguals.

---

3.4. Release from PI

A 2 x 2 x 4 factorial MANCOVA was conducted with two between-subjects variables (age group and language group), the within-subjects variable of list (Lists 1–4), and two dependent variables, proportion of words correctly recalled per list and proportion of intrusions per list. Intrusions occurred when words from one list were 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(3, 311) = 2.12, p = .15, nor were there significant differences between monolinguals and bilinguals, F < 1. There was a list effect, F(3, 311) = 14.68, p < .001 (see Fig. 2A). Bonferroni-adjusted pairwise comparisons indicated that participants as a whole recalled more words correctly on List 1 compared to List 2, p = .01, and List 3, p = .003. Performance was also significantly greater on List 4 than Lists 2 and 3 (p < .001 for both comparisons), which supports the release from PI. There were no interaction effects, nor was MINT performance a significant covariate, F < 1.

Younger adults had significantly fewer intrusions than older adults, F(1, 311) = 15.40, p < .001. Again, there was a main effect of List, F(3, 311) = 9.98, p < .001. Bonferroni-adjusted pairwise comparisons revealed that participants as a whole demonstrated significantly more intrusions on List 2, p = .04, and List 3, p < .001, compared to List 1. Participants also had fewer intrusions on List 4 in comparison to List 3, p < .001, again supporting release from PI. There was also an age-by-list interaction, F(3, 311) = 2.92, p = .03. Only the older adults showed greater interference (defined as more intrusions) on List 2, t(81) = −3.39, p = .002, and List 3, t(81) = −4.65, p < .001, compared to List 1 (see in Fig. 2B). 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 Lists 3 and 4, _t_ (81) = 2.84, _p_ = .007, suggesting the younger adults experienced release from interference. There were no differences between bilinguals and monolinguals with regard to intrusions, _F_ (1, 311) = 1.68, _p_ = .20, nor were there any other interaction effects, _F_ < 1. English MINT score was not a significant covariate, _F_ < 1.

3.5. Correlation between memory tasks

Because both the directed forgetting and release from PI tasks were chosen for the present study under the assumption that these tasks measure resistance to PI, bivariate correlation analyses were performed between the tasks’ outcome measures. For the directed forgetting task, performance was quantified in two ways: the proportion of TBF words retrieved (higher proportion = better performance), and the proportion of TBF words retrieved (lower proportion = 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, the difference between the number of List 3 and 4 intrusions.

When correlating the directed forgetting and release from PI measures across the entire sample, none of the relationships were significant ( _p_ > .50 for all correlations). However, when the sample was divided by language group (collapsed across age), two 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 (see Fig. 3). It appears that the better the bilinguals did at accurately retrieving the TBR words on the directed forgetting task, the less interference they experienced in the release from PI task.

3.6. Structural MRI findings

3.6.1. 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. eTIV was included as a covariate to correct for head size differences. To account for multiple comparisons in the ROI analyses, a false discovery rate (FDR)-corrected significance cutoff of _p_ < .05 was used.

eTIV was a significant covariate for all predictors, _p_ < .001. There was a significant main effect of age for all eight comparisons, such that younger adults had greater GMV in each ROI (see Table 2 for means) as well as across cortical grey matter ( _M_ _young_ = 496,086 mm³, _SE_ = 3209, _M_ _old_ = 435,763 mm³, _SE_ = 4016) and whole-brain grey matter ( _M_ _young_ = 668,829 mm³, _SE_ = 3987, _M_ _old_ = 589,597 mm³, _SE_ = 4990) compared to younger adults had greater GMV in each ROI (see Table 2 for means) as well as across cortical grey matter ( _M_ _young_ = 496,086 mm³, _SE_ = 3209, _M_ _old_ = 435,763 mm³, _SE_ = 4016) and whole-brain grey matter ( _M_ _young_ = 668,829 mm³, _SE_ = 3987, _M_ _old_ = 589,597 mm³, _SE_ = 4990) compared to younger adults.

Table 2

<table>
<thead>
<tr>
<th></th>
<th>Younger Adults</th>
<th>Older Adults</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Monolingual</td>
<td>Bilingual</td>
</tr>
<tr>
<td>Left ACC</td>
<td>4902 (142)</td>
<td>4372 (142)</td>
</tr>
<tr>
<td>Right ACC</td>
<td>4775 (127)</td>
<td>4434 (127)</td>
</tr>
<tr>
<td>Left IFG</td>
<td>12227 (202)</td>
<td>11971 (201)</td>
</tr>
<tr>
<td>Right IFG</td>
<td>12275 (168)</td>
<td>11886 (168)</td>
</tr>
<tr>
<td>Left MFG</td>
<td>24234 (476)</td>
<td>23145 (475)</td>
</tr>
<tr>
<td>Right MFG</td>
<td>24368 (442)</td>
<td>22831 (441)</td>
</tr>
</tbody>
</table>

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

3.6.2. Cortical thickness

Group comparisons of whole-brain and ROI cortical thickness were conducted using a $2 \times 2$ MANCOVA. 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-adjusted significance cutoff of $p < .05$ was adopted for the ROI analyses.

All seven tests showed a significant age effect, $p < .001$, with younger adults having thicker cortex in each of the six ROIs, as well as across the entire cortical surface. There was a main effect of language group for whole-brain cortical thickness, $F(1, 78) = 12.81, p = .004$, such that the monolinguals had thicker cortex than the bilinguals. This was also observed across several ROIs: left ACC, $F(1, 78) = 6.24, p = .02$, left IFG, $F(1, 78) = 14.96, p < .001$, right IFG, $F(1, 78) = 9.59, p = .005$, left MFG, $F(1, 78) = 8.63, p = .006$, and right MFG, $F(1, 78) = 10.15, p = .005$. There was no significant language group effect for right ACC, nor were there any interaction effects, $F_s < 1$ for each ROI. Means for group comparisons can be found in Table 3.

3.6.3. Corpus callosum

A $2 \times 2$ MANCOVA was conducted to determine if differences in corpus callosum volume existed between the four groups. eTIV was included as a covariate in all analyses, and an FDR-corrected significance threshold of $p < .05$ was used.

There was a main effect of age for three corpus callosum parcels; 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, $F(1, 77) = 5.88, p = .03$. Young adults showed greater volume than the older adults in each case. No main effects of language group were evident, $F < 1$ for all parcellations. However, there was an interaction between age and language group for the central segment of the corpus callosum only, $F(1, 77) = 9.87, p = .01$. Among the younger adults, monolinguals ($M = 699.2$ mm$^3$, $SD = 112.3$) had greater volume than the bilinguals ($M = 599.8$ mm$^3$, $SD = 128.9$), but among the older adults, bilinguals ($M = 519.5$ mm$^3$, $SD = 116.0$) had greater volume compared to the monolinguals ($M = 458.6$ mm$^3$, $SD = 83.2$; see Fig. 4). Post-hoc analyses 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, $p > .20$.

3.6.4. Control regions

A $2 \times 2$ MANCOVA 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 differed in the cortical thickness of their left precentral gyrus.

Table 3

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

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

![Fig. 4](image-url) Young adult monolinguals have significantly greater volume in the central segment of the corpus callosum compared to young adult bilinguals, but older monolinguals have less volume compared to older bilinguals. Error bars represent standard deviation.

(M$_{monolingual} = 2.65$ mm, $SD = 0.19$; $M_{bilingual} = 2.57$ mm, $SD = 0.19$), $F(1, 78) = 8.24, p = .005$, right precentral gyrus ($M_{monolingual} = 2.59$ mm, $SD = 0.17$; $M_{bilingual} = 2.53$ mm, $SD = 0.19$), $F(1, 78) = 5.31, p = .02$, and left postcentral gyrus ($M_{monolingual} = 2.10$ mm, $SD = 0.12$; $M_{bilingual} = 2.04$ mm, $SD = 0.12$), $F(1, 78) = 6.91, p = .01$, with monolinguals displaying thicker cortex in each case. There were no interaction effects, $p > .10$ for all comparisons.

While the supplementary motor area (SMA) and pre-SMA have been implicated previously in bilingual language processing (Abutalebi et al., 2012; Meschyan and Hernandez, 2006), no prior studies have observed differences between monolinguals and bilinguals in primary motor cortex, which is why it was chosen a priori as a control region. Given that the monolingual sample also had greater cortical thickness in left ACC, bilateral IFG, and bilateral MFG compared to bilinguals, we wanted to make sure this finding was not a result of an overall language group confound. Two additional control regions were considered, the cuneus and pericalcarine cortex. GMV and cortical thickness were examined in each of these regions bilaterally. There were no significant main effects or interactions in any of these four regions, signifying no generalized differences in cortical volume or thickness between monolinguals and bilinguals in the present sample.

3.7. TBSS findings

3.7.1. Whole brain analysis

A $2 \times 2$ between-subjects ANOVA only revealed that younger adults had greater white matter integrity (defined as the FA at each voxel in the mean FA skeleton) across the majority of the FA skeleton compared to the older adults, $p < .05$. There were no significant clusters of voxels that differed between bilinguals and monolinguals or any interaction effects.

3.7.2. ROI analysis

We predicted that white matter integrity in tracts underlying frontal memory regions, such as the cingulum, SLF, and corpus callosum, might show patterns of greater FA for bilinguals compared to monolinguals. To investigate this further, $2 \times 2$ 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 corpus callosum ROI, 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 comparisons. However, there were no differences between monolinguals and bilinguals nor any interactions, $p > .10$ for all other comparisons for these ROIs.
3.8. Brain-behavior relationships

We also examined the relationship between participants’ brain structure and resistance to PI performance. All tests were subject to an FDR or TFCE correction for multiple comparisons. After controlling for age (and eTIV where applicable), GMV, cortical thickness, and corpus callosum volume were not significantly related to directed forgetting or resistance to PI performance. Whole-brain FA was also not significantly related to behavioral outcomes.

However, when examining relationships between individual white matter tracts of interest and resistance to PI measures, some interesting findings emerged. Across the whole sample, there was a negative relationship between TBF recall and splenium FA, such that higher FA predicted better performance (fewer TBF words recalled), \( p = .05 \). The relationship remained when examining just the bilinguals, collapsed across age, \( p = .03 \). When examining the monolinguals only, splenium FA did not predict fewer TBF words recalled, \( p = .50 \), but UF FA did, \( p = .01 \), 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, and these findings may be consistent for each language group regardless of age.

With regard to the release from PI task, both left and right UF FA negatively predicted buildup of interference for the whole sample (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 lower integrity in bilateral UF. These tracts connect the prefrontal regions associated with resistance to PI (e.g., the IFG) to parts of the anterior temporal lobe, including parahippocampal areas. When the sample was separated by language group (again collapsed across age), this relationship was still present for the monolinguals (\( p = .03 \) for left UF, \( p = .02 \) for right UF), but not for the bilinguals (\( p = .13 \) for left UF, \( p = .46 \) for right UF). Right SLF FA negatively predicted release from interference across all participants, \( p = .004 \), implying that the poorer the white matter integrity in the participant’s right SLF, the greater the improvement in recall performance between List 3 and List 4 (in other words, the lower recall performance was on List 3). This relationship was also significant for just the bilinguals, \( p = .01 \), but not the monolinguals, \( p = .18 \).

4. Discussion

Whether being bilingual provides any advantages to memory, and specifically resistance to PI, is a topic largely ignored in the bilingualism literature to date. 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 study. We assessed cognitive performance differences between older and younger adults and between monolinguals and bilinguals, and 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 in GMV, monolinguals displayed thicker cortex in left ACC, bilateral IFG, and bilateral MFG. In addition, although no language group differences were evident in FA, monolinguals had greater volume in the central corpus callosum among the young adults, but less volume among the older adults. Brain structure also predicted behavioral performance uniquely for the two language groups. Splenium FA was negatively associated with directed forgetting performance (TBF recall) for the bilinguals, while bilateral UF FA was negatively associated with TBF recall for the monolinguals.

4.1. Evaluation of predictions

Our predictions for the older adults were derived from the comparison of two theoretical frameworks. The first was the brain reserve hypothesis, which suggests that some individuals have brains resilient to the effects of aging, resulting in slower rates of neural decline. Cognition will remain intact until some atrophic threshold is reached; at that point, both brain structure and the supported cognitive processes begin to decline in tandem. By contrast, the cognitive reserve hypothesis suggests that brain and behavior do not have to decline in tandem. Instead, cognitive performance can remain intact despite brain atrophy, and cognition will remain buoyant as a function of other cognitively demanding activities the individual has been subject to throughout their life. It has been suggested that using two languages on a regular basis might act as one of the cognitively demanding activities that preserves cognition during aging (Gold et al., 2013; Luk et al., 2011; Valian, 2015).

The only significant group difference on the directed forgetting task was better TBR recall among the young adults compared to the older adults. This was expected, as memory performance typically declines across the lifespan (Hedden and Gabrieli, 2004). On directed forgetting tasks, older adults tend to remember significantly more TBF words than young adults, which is often interpreted as a sign of poorer attentional control and worse resistance to PI (Campbell et al., 2012; Weeks and Hasher, 2018). However, this pattern was not evident in the present study. It is possible that the amount of time allocated for the distractor task between encoding and recall may have been too long, resulting in more forgetting than anticipated, or 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 (5 min in the study by Sego et al., compared to 3 min here).

Another possible explanation may be that our TBF condition 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 older adults generally display worse performance on directed forgetting tasks because they experience greater attentional broadening and are more easily distracted than young adults. They found 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 were told to remember one item (such as the picture) while ignoring the other item (the word). Thus, introducing a condition where greater attentional resources are required to sort between relevant and irrelevant stimuli might induce larger behavioral differences between younger and older adult participants, especially for TBF words. Of course, it is also plausible that there were truly no differences between the younger and older adults in our sample. More research should be done to clarify this issue.

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. No differences on either correct recall or intrusions emerged between the bilinguals and monolinguals for either age group.

For both tasks, there were no differences between the older bilinguals and monolinguals. 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 regions that support resistance to PI performance, the older monolinguals had significantly thicker cortex than the older bilinguals in bilateral IFG and MFG. These findings support cognitive reserve, because matched cognition between groups and comparable performance on various behavioral tasks is coupled with cortical thickness 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. Similar results have been seen previously (Gold et al., 2013); bilingual and monolingual older adults were matched on a series of neuropsychological tasks, but the bilinguals demonstrated lower white matter integrity. Gold and colleagues did not examine cortical thickness, so it is possible their bilinguals were also...
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experiencing greater cortical thinning. Our results are also compatible with the Bilingual Anterior to Posterior Subcortical Shift model (Grundy et al., 2017), which suggests that bilinguals rely less on anterior brain regions as they age. Thus, the present findings suggest that knowing a second language does provide protective benefits to older adult bilinguals, though such advantages might not be evident when examining behavior alone. This is why it is important to study brain and behavior in tandem to uncover links between cortical structure and cognitive performance.

While cognitive reserve explains the grey matter differences between older bilinguals and monolinguals, the white matter data suggest a pattern of brain reserve. Though direct group comparisons did not yield significant FA differences between older bilinguals and monolinguals (cf. Luk et al., 2011), correlational analyses showed that in certain instances bilinguals exhibited significant relationships between FA and behavior, with greater FA in the splenium and SLF typically indicating better resistance to PI performance. In the few instances in the present study 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 to maintain cognitive performance. Additionally, bilingual older adults displayed greater volume in the central corpus callosum than monolinguals. Together, these results indicate the older adult bilinguals may be exhibiting evidence of both brain reserve (in the white matter) and cognitive reserve (in the grey matter) as a function of knowing two languages. Such findings suggest that more intact white matter may be supporting cognitive preservation among the older bilinguals, while their grey matter is more prone to the typical structural declines that occur with age.

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). The present findings differ from the previous work in two important ways. First, Duncan et al. (2018) focused on the cognition and brain structure of multilinguals diagnosed with varying degrees of cognitive impairment, while the current study only tested cognitively healthy bilinguals. Second, their study only focused on grey matter, whereas the current results suggest an independence of cognitive and brain reserve mechanisms as a function of grey versus white matter. To our knowledge, no other studies have found these results in the same group of healthy bilingual individuals. The present study is the first to investigate how cognitive performance relates to both grey and white matter integrity in older bilinguals and has yielded novel findings that can aid in understanding how bilingual and monolingual brains differ in old age.

Among the younger adults, there were no significant differences between the monolinguals and bilinguals on the directed forgetting or release from PI tasks. Differences in behavioral performance between cognitively healthy young adult bilinguals and monolinguals are infrequent, since young adulthood is considered the “peak” age for cognition including executive control and resistance to PI. Additionally, past research on resistance to PI performance in bilinguals has suggested differences between bilingual and monolingual young adults emerge only if controlling for vocabulary knowledge (Bialystok and Feng, 2009), since bilinguals tend to have smaller vocabularies in each language compared to a monolingual’s vocabulary. However, vocabulary performance (measured via the English MINT score) was not a significant predictor of the present analyses, likely because nearly all the bilinguals in this study were highly proficient in both languages. Therefore, the lack of cognitive differences is not surprising. The only distinctions that emerged unique to the young adults were regarding brain structure: a difference in average thickness across the cortical mantle, in left IFG thickness, and in volume of the central corpus callosum. Young monolinguals displayed greater thickness and volume than the young bilinguals. This contradicts previous findings showing greater left IFG thickness in early bilinguals compared to monolinguals (e.g., Klein et al., 2014).

One possibility for these divergent findings could be differences in language experience. In the present study, nearly all the bilinguals were highly proficient early sequential bilinguals who learned one language (typically Spanish) from birth and began learning their second language usually by age five. Klein’s participants were also early sequential bilinguals, but their second language (L2) proficiency was not as high (mean self-report rating = 5.4/7; Klein et al., 2014). Alterations to cortical grey matter may be most prevalent during initial learning stages of second language acquisition and in contexts where participants are not continually immersed in their L2 environment (Platsikas, 2020). Although Klein’s participants resided in a bilingual city, it is likely the participants varied quite a bit in their amount of exposure to and immersion in their L2. Our bilingual participants have been immersed in their L2 (English) for the majority of their lives, and in many instances it has become their dominant language. Thus, any cortical changes present early in second language learning may diminish once bilinguals become highly proficient in both languages and use both languages regularly (Platsikas, 2020).

It is interesting that the present data suggest the bilingual young adults show smaller or thinner brain structures. One hypothesis suggests previously for explaining thinner cortex among young adults is the notion that underlying white matter expands throughout development and pushes up like a balloon against the cortex, stretching and subsequently thinning the grey matter (Hogstrom et al., 2013; Aleman-Gomez et al., 2013). While there were no FA differences between young adult monolinguals and bilinguals, 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.

The results reported herein are in line with the Dynamic Restructuring Model, a recent theory proposed by Platsikas (2020) that strives to unify the seemingly disjointed and disparate literature surrounding the bilingual brain. He proposes three stages that the brain experiences in the process of learning and maintaining a second language. The first is initial exposure; this stage encompasses grey matter changes typically seen when individuals are learning a second language. In the second stage, consolidation, grey matter alterations renormalize, likely due to pruning occurring from greater efficiency of the regions and networks necessary for maintaining and controlling use of one’s two languages (Platsikas, 2020). Platsikas also suggests these efficient connections that remain after learning could be the same connections that retain their integrity once age-related cortical decline sets in. This may be why white matter differences such as greater FA are more prevalent in bilinguals with more experience with their L2 (e.g., Kuhl et al., 2016; Mamiya et al., 2016; Mohades et al., 2012). Stage 3, the peak efficiency stage, is less defined. Platsikas suggests longitudinal examinations of bilinguals across their lifetime are necessary 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 the present study where grey matter volume or cortical thickness was greater in the bilinguals than monolinguals, the Dynamic Restructuring Model would posit that the bilinguals in the current sample had already moved through Stage 1 and entered Stage 2. While in the older adults 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. 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 the bilinguals, which could be a function of continually juggling two languages. No conclusions about Stage 3 can be drawn since no longitudinal data was collected. Thus, it appears the findings herein do corroborate some of the key tenets of the Dynamic Structuring Model (Platsikas, 2020).
4.2. Relationships between tasks

We expected the two resistance to PI tasks, directed forgetting and release from PI, to be correlated. Surprisingly, the outcome measures were not significantly related across the entire sample. However, when the correlations were considered separately for monolinguals and bilinguals, the bilinguals showed negative relationships between TBR word recall and buildup of intrusions, as well as TBR word recall and release from intrusions, suggesting that better TBR performance is related to less interference on the release from PI task for the bilinguals only.

Friedman and Miyake (2004) used a Brown-Peterson variant to test resistance to PI, which is very similar to the release from PI task used in the current study. Directed forgetting is also considered a measure of resistance to PI, especially in studies examining inhibitory decline in older adults (Jogge et al., 2008; Titiz and Verhaeghen, 2010; Weeks and Hasher, 2018; Zacks et al., 1996; see Bisset et al., 2009, for directed forgetting done with younger adults). Interestingly, no prior study to our knowledge has used both release from PI and directed forgetting to test resistance to PI within the same sample. Thus, it is unclear whether the two tasks are truly measuring resistance to PI in the same way. More research is needed to explore this possibility.

It is also important to remember that there are different versions of directed forgetting. 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 word. In a list-method version, participants see an entire list of words and are told after encoding to remember or forget the list. In an item-method task, participants are cued to forget after about 3 s of rehearsal, whereas in a list-method version, some items may be rehearsed for upwards of a minute, making them less susceptible to forgetting. Therefore, list-method directed forgetting may correlate more strongly with release from PI, since each word is rehearsed for a longer time and could be more susceptible to being remembered, even under explicit “forget” orders.

Knowing that directed forgetting and release from PI tasks might not measure exactly the same executive control construct, why was there a relationship among task outcomes for the bilinguals but not for the monolinguals? Both buildup of and release from intrusions indicate how much PI is present across each list, with lower scores on each being indicative of better executive control. On the other hand, TBR recall is a reflection of better episodic memory (Titiz and Verhaeghen, 2010). Therefore, it is possible that for the bilinguals, executive control and memory performance are more tightly linked than for monolinguals. Perhaps using two languages results in more frequent utilization of memory resources (e.g., remembering, and then selecting, which language to speak in a particular context), and requires increased connectivity between the regions underlying these processes — something the monolinguals would not need to maintain. This possible interpretation should be tested in future work.

4.3. Limitations and future directions

While a few limitations of the current study have already been addressed in the preceding sections, there are still several points worth mentioning. First, this study utilized a cross-sectional design, limiting the ability to draw strong conclusions about changes to brain structure or resistance to PI abilities over time. In the future, it would be ideal to follow bilinguals and monolinguals longitudinally in order to assess how patterns of neural or cognitive alteration might differ between groups across the adult lifespan. Further, the present study did not include functional imaging data. Thus, it is unclear how the bilinguals and monolinguals (and younger vs. older adults) might have differed with regard to neural activity and efficiency during the two behavioral tasks and whether the functional data would also support a reserve account. While we report significant relationships between behavioral performance and structural integrity, these findings are of course not causal, and we cannot conclude that structural changes in the bilingual brain may be influencing behavioral performance (or vice versa) until the brain-behavior relationship is fully elucidated with the addition of a functional imaging measure.

As mentioned previously, nearly all the bilinguals were highly proficient early bilinguals. In addition, the majority of the bilinguals were heritage speakers: while in general they learned Spanish first, they identified as more proficient in English. Thus, the present findings may or may not generalize to bilinguals with different linguistic experiences, such as late acquisition of a second language or living in an immersive environment where the bilingual must speak the less dominant language. Additionally, we only tested Spanish-English bilinguals, so it is unclear how bilinguals of other language combinations might perform on these tasks. In general, though, past research on cognition has suggested that findings among bilinguals who speak different languages are fairly consistent, and it is not the language per se influencing performance, but the cognitive control required to manage both languages in one brain (Bialystok, 2017).

Regarding the resistance to PI tasks, both directed forgetting and release from PI would typically 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 (Jonides et al., 2000; Nee et al., 2007). Only release from PI has been used in previous work to test resistance to PI abilities in bilinguals compared to monolinguals (Bialystok and Feng, 2009); this study is the first to use directed forgetting to assess bilingual and monolingual differences in resistance to PI, and no studies have compared bilingual and monolingual performance on a working memory-based resistance to PI task. Therefore, this would be an important step forward to add to the relatively small body of work examining resistance to PI in bilinguals.

Finally, prior bilingualism work has suggested that learning a new language intensively over a brief time period stimulates brain structure changes (Hosoda et al., 2013; Martensson et al., 2012; Stein et al., 2012) and increases proficiency in the L2 (White et al., 2012), though there are few, if any, studies to date that have examined domain-general changes to behavior as a function of intensive second language acquisition. An important follow-up would be to examine how short-term language training might lead to behavioral adaptations in all aspects of cognition but particularly for resistance to PI. While in the current study bilinguals and monolinguals did not show behavioral differences on the resistance to PI tasks, when the bilinguals were first acquiring their L2, rapid neural changes likely occurred as a result of this new learning (Lovden et al., 2013; Platsikas, 2020), and it is quite possible that these changes were coupled with short-term enhancements in cognitive abilities. Since the bilinguals in the present study were already proficient in both languages and had been actively using both for many years or decades, any neuroanatomical changes that resulted as a function of learning and experience could have already renormalized, and cognition may have stabilized as well. Short-term second language training can provide longitudinal insights into how cognitive abilities change as a function of learning another language. 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 et al., 2012), and the acquisition of a second language appears to support grey matter increases in cortical regions important for language processing and resistance to PI (Platsikas, 2020). While behavioral differences were not present in the current study, likely due to the participants’ lifelong experience with juggling multiple languages, it is still unclear how the early stages of the language learning might impact resistance to PI performance.

4.4. Final thoughts and conclusions

Over the past two decades, there has been a surge in the number of...
studies that have examined bilingualism and how bilinguals differ from monolinguals, both behaviorally and with regard to brain structure. That said, it is interesting to consider how these studies have been framed over time. They are often designed in a way that perpetuates the idea that monolingual cognition and brain organization is the norm. 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 present findings could not be framed in this way. For example, 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 executive control) as a function of only relying on one language rather than managing two. 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.

Ultimately, this study is the first to demonstrate both cognitive reserve and brain reserve in distinct neural indices (grey matter and white matter, respectively) within the same group of healthy bilingual participants. Not only does lifelong bilingualism seem to preserve cognitive performance in the face of cortical atrophy, but it also seems to moderate the relationship between white matter integrity and cognitive performance. Overall, it appears that bilingualism is providing neural and cognitive protection that supports important structural links between the brain regions underlying executive control, memory, and language processes.

Credit author statement

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