How Proactive Interference during New Associative Learning Impacts General and Specific Memory in Young and Old

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Abstract

■ Some prior research has found that older adults are more susceptible to proactive interference than young adults. The current study investigated whether age-related deficits in pFC-mediated cognitive control processes that act to detect and resolve interference underlie increased susceptibility to proactive interference in an associative memory task. Young and older adults were scanned while tasked with remembering which associate (face or scene) objects were paired with most recently during study, under conditions of high, low, or no proactive interference. After scanning, participants' memory was tested for varying levels of episodic detail about the pairings (i.e., target category vs. specific target category vs. specific target associate). Young and older adults were similarly susceptible to proactive interference. Memory for both the general target category and the specific target associate worsened as the level of proactive interference increased, with no robust age differences. For both young and older adults, the left ventrolateral pFC, which has been indicated in controlled retrieval of goal-relevant conceptual representations, was sensitive to increasing levels of interference during encoding but was insensitive to associative memory accuracy. Consistent with the Compensation-Related Utilization of Neural Circuits Hypothesis model of cognitive aging, the ventromedial pFC, which is involved in the monitoring of internally generated information, was recruited more by older than young adults to support the successful retrieval of target–object pairs at lower levels of proactive interference. Collectively, these results suggest that some older adults are able to engage in the cognitive control processes necessary to resolve proactive interference to the same extent as young adults. ■

INTRODUCTION

It is well established that advancing age is associated with declines in a number of cognitive functions. Perhaps the most noticeable declines are seen in episodic memory tasks, including associative memory (for a review, see Mitchell & Johnson, 2009; Old & Naveh-Benjamin, 2008). Associative memory is the ability to learn and remember the relationship between multiple items, such as people, events, objects, and places. Previous neuroimaging studies have found that associative memory performance is supported by prefrontal cortex (pFC) and core episodic network including the medial temporal lobe (MTL; for a review, see Sestieri, Shulman, & Corbetta, 2017; Monti et al., 2015; Mitchell & Johnson, 2009; Eichenbaum, Yonelinas, & Ranganath, 2007; Simons & Spiers, 2003). Some evidence suggests that older adults' impaired associative memory performance may be because of underrecruitment of the MTL, including the hippocampus, relative to young adults (Cansino et al., 2015; Dennis, Kim, & Cabeza, 2008). However, evidence demonstrating that older adults recruit the MTL to the same extent as young adults when task performance

is matched (de Chastelaine, Mattson, Wang, Donley, & Rugg, 2015, 2016; Angel et al., 2013; Rugg & Morcom, 2005) suggests the MTL is not the major contributor to the age-related impairments seen in associative memory. Rather, it is more likely that these age-related impairments are because of pFC dysfunction (Duarte & Dulas, in press). Indeed, previous studies have shown age-related declines in pFC activity during both encoding (Dulas & Duarte, 2011; Dennis, Hayes, et al., 2008) and retrieval (McDonough & Gallo, 2013; Dulas & Duarte, 2012; Rajah, Languay, & Valiquette, 2010) despite age-equivalent MTL recruitment, even when memory performance is equated between age groups (de Chastelaine et al., 2016; Dulas & Duarte, 2014). Collectively, these findings are consistent with the "frontal aging hypothesis," which suggests that pFC dysfunction underlies many age-related cognitive impairments including episodic memory (West, 1996).

One contributing factor to age-related associative memory impairments may be increased susceptibility to proactive interference and reduced recruitment of pFC-mediated cognitive control processes that resolve it. Proactive interference occurs when previous, but no longer valid, information interferes with the learning and retrieval of new information. For example, misremembering

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your new phone password may be because of a strong memory of your previous phone password. Previous research suggests that older adults are more susceptible to proactive interference than young adults. They have impaired performance in tasks with proactive interference in working memory (Lustig & Jantz, 2015; Pettigrew & Martin, 2014; Emery, Hale, & Myerson, 2008; Bowles & Salthouse, 2003; Lustig, May, & Hasher, 2001; Jonides et al., 2000; May, Hasher, & Kane, 1999) and episodic memory (Wahlheim, 2014; Healey, Hasher, & Campbell, 2013; McDonough & Gallo, 2013; Ikier, Yang, & Hasher, 2008). For example, in a working memory task, Jonides et al. (2000) presented young and older adults with a set of four target letters. After a short retention period, they were then presented with a single probe letter and asked to respond with whether or not the letter was in the presented set. Importantly, some probe letters were recently presented, but not in the critical set of four, thereby inducing proactive interference. Older adults were disproportionately affected by this interference with slower RTs and lower accuracy than younger adults. Despite the abundance of studies investigating proactive interference in episodic and working memory, older adults' susceptibility to proactive interference in associative memory has not been thoroughly investigated. Of the research that has been conducted, results are somewhat mixed, with some finding no age differences (Dulas & Duarte, 2016; Guez & Naveh-Benjamin, 2016), whereas others showing greater susceptibility to proactive interference in older adults than young adults (Burton, Lek, Dixon, & Caplan, 2019; Ebert & Anderson, 2009; Jacoby, Bishara, Hessels, & Toth, 2005).

As pFC-dependent cognitive control operations have been implicated in detection and resolution of proactive interference, it is reasonable to predict that age-related underrecruitment of these processes could contribute to older adults' susceptibility to proactive interference when observed. Post-retrieval selection is a process that resolves competition between multiple active representations (for a review, see Badre & Wagner, 2007; Moss et al., 2005; Fletcher, Shallice, & Dolan, 2000). Specifically, after sought-after information is retrieved, relevant information is enhanced and irrelevant information is suppressed. Older adults' poor performance on proactive interference tasks may be because of a failure to engage this selection process, which has been described as a failure to engage in inhibitory processing (Hasher, Quig, & May, 1997; Connelly, Hasher, & Zacks, 1991; Hartman & Hasher, 1991). Post-retrieval monitoring is a process of evaluating and manipulating retrieved information when someone is close to their decision criterion (Henson, Rugg, Shallice, & Dolan, 2000). Behavioral studies have shown that older adults have worse performance on tasks that place high demand on post-retrieval monitoring (for a review, see Mitchell & Johnson, 2009).

Numerous neuroimaging studies have tied post-retrieval selection to the left ventrolateral pFC (VLPFC;

for a review, see Badre & Wagner, 2007). Both lesion (Thompson-Schill et al., 2002) and TMS (Wais, Kim, & Gazzaley, 2012; Feredoes, Heinen, Weiskopf, Ruff, & Driver, 2011) studies have indicated that disruption of the left VLPFC results in longer RTs and a higher percentage of errors in proactive interference working memory tasks. By contrast, the right VLPFC has been more often implicated in tasks with motor inhibition demands or decision uncertainty (Levy & Wagner, 2011). Working memory fMRI studies have found that the left VLPFC is recruited more to probes with high than low interference (for a review, see Badre & Wagner, 2007). However, these studies have only investigated correct trials and not how the left VLPFC contributes to the successful resolution of proactive interference. A few semantic interference studies have found that the left mid-VLPFC is recruited proportionally with increasing levels of interference but does not differentiate between correct and incorrect trials (Han, O'Connor, Eslick, & Dobbins, 2012; Atkins & Reuter-Lorenz, 2011). Collectively, these results suggest that the left VLPFC is sensitive to the level of interference, but not to the successful resolution of interference. By contrast, the dorsolateral pFC (DLPFC), a region often implicated in post-retrieval monitoring (Achim & Lepage, 2005; Mitchell, Johnson, Raye, & Greene, 2004; Lepage, Brodeur, & Bourgouin, 2003; Rugg, Henson, & Robb, 2003; Fletcher & Henson, 2001; Henson et al., 2000; Henson, Shallice, & Dolan, 1999; Shallice et al., 1994), has been found to be sensitive to the successful resolution of interference, differentiating correct from incorrect decisions for high-interference conditions (Dulas & Duarte, 2016; Atkins & Reuter-Lorenz, 2011; Öztekin, Curtis, & McElree, 2009). Taken together, these results suggest that post-retrieval selection and post-retrieval monitoring contribute to the detection and resolution, respectively, of proactive interference across episodic and nonepisodic memory tasks.

In a previous study, we investigated age-related changes in these pFC-mediated cognitive control processes recruited during retrieval of associative memories with varying levels of proactive interference (Dulas & Duarte, 2016). In this task, young and older adults studied objects paired with associates (either a face or a scene) under high and low associative proactive interference. We found that proactive interference impaired associative memory accuracy equally for young and older adults. We found that the left VLPFC was sensitive to the level of interference but did not directly contribute to accurate memory retrieval. The left DLPFC/anterior pFC, however, was sensitive to successful associative memory retrieval for high-interference trials, but for young adults only. We have since replicated this dissociation between age effects along the anterior–posterior axis of pFC, with more age-related sparing of posterior pFC (i.e., VLPFC) than anterior pFC recruitment during episodic memory tasks (James, Rajah, & Duarte, 2019; Dulas & Duarte, 2014). We propose that age-related pFC dysfunction may not

be ubiquitous but particularly evident for the "high-order" control processes supported by more anterior regions (Duarte & Dulas, in press).

Although our previous findings suggest that age-related associative memory impairments may not be attributed to increased susceptibility to proactive interference, some aspects of our previous study may have reduced any age-related susceptibility to it. The two-stage forced-choice design employed during retrieval could have allowed participants to base their associative memory decisions on familiarity rather than recollection. It is possible that participants may have chosen associate category over the other, not necessarily because they recollected that the object was paired with a specific face or scene but rather that the face or scene category was more familiar given that it was more recently encoded. That is, temporal recency decisions often depend on monitoring relative trace strength or familiarity rather than recollection (Rajah & McIntosh, 2006; Mitchell et al., 2004; Dobbins, Rice, Wagner, & Schacter, 2003). Although the forced-choice category judgment was similar to source memory tasks in many previous studies, it is well known that such decisions can be familiarity based (Bastin & Van der Linden, 2003; Norman & O'Reilly, 2003; Yonelinas, 1999) and, consequently, familiarity may contribute to source memory accuracy. Aging is well known to disproportionately impact recollection more than familiarity (Prull, Dawes, Martin, Rosenberg, & Light, 2006; Light, Prull, La Voie, & Healy, 2000), and older adults may rely on familiarity to make forced-choice memory decisions (Bastin & Van der Linden, 2003). A possible reliance on familiarity could also explain the marginal impairment ($p = .06$) in older adults' associative memory performance. In the current study, we modified the associative retrieval task to reduce any potential reliance on familiarity. Young and older adults studied objects paired with either a face or a scene with varying levels of proactive interference from the other associated category. However, during test, rather than having participants choose between a presented face or scene associate, they were asked to choose whether the recent pairing was from the face or scene category, followed by more specific memory decisions (i.e., the specific category [male/female/indoor/outdoor] and the exact face or scene) to probe recollection directly. This is under the premise that recollection of specific details is likely needed to accept the target face/scene and reject the highly familiar competitors (Migo et al., 2014). In addition, unlike our previous study in which we assessed pFC control contributions to associative memory retrieval only, here, we assess these processes during new associative learning as well. We predicted the following:

1) Behaviorally, we predict that, for both age groups, associative memory accuracy will decrease with increasing levels of proactive interference and that older adults will have worse associative memory performance than

young adults, specifically under conditions of high interference.

2) At retrieval, the left VLPFC will be sensitive to increasing levels of interference but insensitive to the resolution of interference (i.e., accuracy). The DLPFC, on the other hand, should be sensitive to the resolution of interference. Given the potential increased reliance on recollection in our retrieval task, we predict age-related underrecruitment of pFC, particularly more anterior pFC regions contributing to interference resolution.

3) Although these pFC-mediated cognitive control processes recruited to resolve proactive interference have been primarily investigated during retrieval, prior research in pFC operations during associative encoding suggest they could operate during encoding as well. The left VLPFC may be sensitive to increasing levels of interference as it has been indicated in selection and control of incoming information during encoding (for a review, see Blumenfeld & Ranganath, 2007). Similarly, the DLPFC may be sensitive to the resolution of interference as it has been indicated to support successful associative encoding through binding and organizing information (for a review, see Blumenfeld & Ranganath, 2007).

METHODS

Participants

The participants for this study were 25 young adults (13 women, aged 18–37 years) and 25 older adults (12 women, aged 60–75 years). Older and younger adults were matched for years of education, $t(48) = 0.413$, $p = .681$. Group characteristics are presented in Table 1. All participants were recruited from the Georgia Institute of Technology and the surrounding Atlanta area. All participants were right-handed, native English speakers, with normal or corrected-to-normal vision (using MRI-compatible glasses when necessary) and with no reports of psychiatric/neurological disorders,

Table 1. Group Characteristics of Participants

Measure	Young (n = 25)	Older (n = 25)
Age	24.44 (5.37)	67.04 (4.44)
Sex	13 women	12 women
Race/ethnicity	9 BL/AA, 7 NHW, 9 NHA	12 BL/AA, 11 NHW, 2 UNK
Education	15.64 (2.23)	15.92 (2.55)
MoCA	27.68 (1.81)	26.52 (2.77)

Standard deviations are in parentheses. BL/AA = Black/African American; NHW = not Hispanic white; NHA = not Hispanic Asian; UNK = unknown.

vascular disease, psychoactive drug use, or claustrophobia. Participants were compensated with class credit or $15 per hour. All participants signed consent forms approved by the Georgia Institute of Technology Institutional Review Board.

Neuropsychological Assessment

After completing the fMRI portion of the study, participants were administered the Montreal Cognitive Assessment (MoCA; Nasreddine et al., 2005) to rule out any cognitive impairments, such as mild cognitive impairment. A score of less than 26 of 30 is the traditional cutoff score for the MoCA. No participants were excluded based on their MoCA scores; however, three young adults who were already familiar with the test were excluded. Three Black/African American older adults scored lower than 26 (scores: 21, 22, and 23) but scored within 2 *SD*s of mean performance on our experimental task. Given that the MoCA has been found to not fairly assess the cognitive status of people from various educational, cultural, and racial backgrounds (Carson, Leach, & Murphy, 2018; Sink et al., 2015; Manly, 2005) and removing these participants did not largely affect our results, we chose to not exclude these three individuals. A previous study in our laboratory found a similar pattern: Black/African American older adults scored low on MoCA but within 2 *SD*s of mean performance on the memory task (Hokett & Duarte, 2019), further providing support that the MoCA may not be the fairest cognitive assessment. Average MoCA scores are presented in Table 1. Older adults' scores were not significantly lower than those of young adults, $t(45) = 1.676$, $p = .101$.

Materials

Two hundred sixteen color photographs of nameable objects taken from Hemera Technologies Photo-Objects DVDs or from the Internet via Google search were used. All images were presented against a gray background. The images were chosen such that each depicted a unique object. In addition, eight images of young adult faces (four male, four female) and eight images of scenes (four indoor, four outdoor) were used as associates for the experiment. The faces were taken from the Max Planck Institute's FACES database (Ebner, Riediger, & Lindenberger, 2010), and the scenes were taken from the SUN database (Xiao, Hays, Ehinger, Oliva, & Torralba, 2010).

Design and Procedure

The study was divided into three phases: encoding, retrieval, and post-retrieval. A practice session was administered before each phase to ensure the participant understood the task. The practice session for encoding and retrieval was administered before the encoding phase to ensure the participant could sufficiently perform the memory task before entering the scanner. The practice session for post-retrieval was administered after the participant exited the scanner and before the post-retrieval task. Only the fourth block of encoding and all of retrieval were scanned. Stimuli were counterbalanced across participants, such that each object appeared in different conditions across participants. Two hundred sixteen objects were studied during encoding, and all 216 objects were later tested at retrieval and post-retrieval. Figure 1 displays the experimental design.

Encoding

The encoding phase was separated into four blocks. The first three were administered outside the scanner, and the fourth was administered inside the scanner. Participants were presented with all 216 objects in each block. For each trial, the participant was presented with an object and either a face or a scene for 3 sec. For half of the participants, the object was presented on the left side of the screen and the face/scene was presented on the right. For the other half of the participants, this was reversed. The participants were asked to rate how easy or hard it is to imagine the items depicted in the images interacting in the real world. While the pairing was presented on the screen, they were asked to respond with their rating using a number pad: "1" if it is easy to imagine the images together, "2" if it is neither easy nor difficult to imagine the images together, and "3" if it is difficult to imagine the images together. While in the scanner, participants responded on a button box with the same response options. For the first three blocks, each trial was followed by a fixation cross for 1 sec. For the fourth block, each trial was followed by an arrow task. The arrow task maximizes design efficiency by pseudorandomly interspersing event trials with "active" baseline trials lasting between 2 and 6 sec, jittered in increments of 2 sec (Dale, 1999). Every 2 sec, an arrow appeared on the screen and participants were asked to respond using a button box to indicate the direction of the arrow: "1" in response to a left-pointing arrow and "2" for a right-pointing arrow. Requiring participants to respond to the arrows kept them engaged in the task and intended to minimize default mode network activity (Stark & Squire, 2001). Immediately after the completion of the first three blocks, participants were taken to the scanner to complete the rest of encoding and retrieval. Each block was pseudorandomized so participants were not presented with more than three trials of the same condition (i.e., high interference, low interference, no interference) in a row. The first three blocks lasted 45 min, with each block lasting 15 min. The fourth block was split up into three parts to give the participant frequent breaks to prevent fatigue; each part lasted 9 min, for a total of 21 min. The total duration of the encoding phase, including practice and setup in the scanner, was 1.5 hr.

Figure 1. Experimental design for the study.
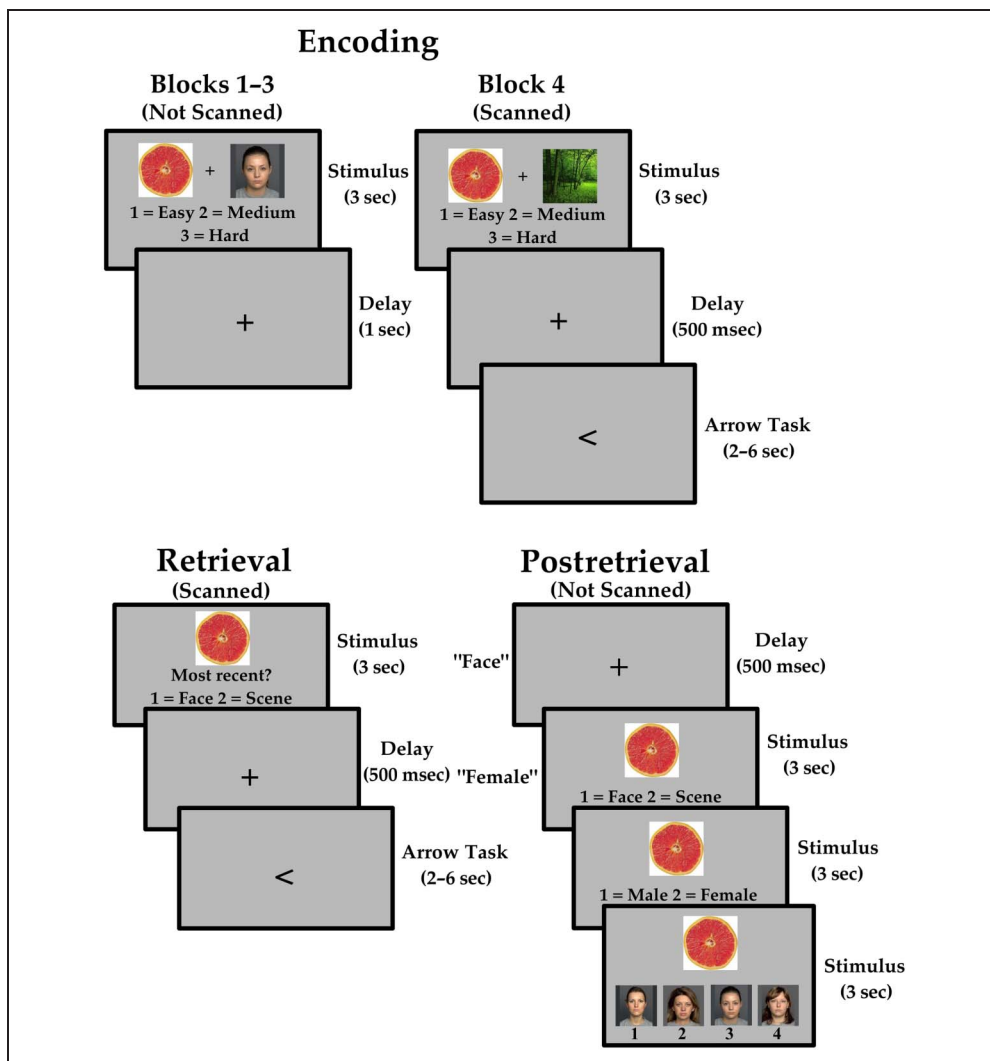
During encoding, objects were evenly divided across the high-interference, low-interference, and no-interference conditions (72 objects per condition). Unfortunately, because of a coding error, 18 young adults and 25 older adults had 60 trials in the low-interference condition. For the high-interference condition, the object was paired with the lure associate for the first two blocks and paired with target associate for the last two blocks. For example, in Figure 1, the grapefruit would have been paired with the female face for Blocks 1 and 2 and then paired with the forest for Blocks 3 and 4. For the low-interference condition, the object was paired with the target associate for three blocks and paired with lure associate for one other block. For the no-interference condition, the object was paired with the target associate for all four blocks. For all three interference conditions, the object was paired with the target associate during the fourth and final block.

Retrieval

After finishing the fourth block of encoding in the scanner, participants immediately began the retrieval phase.

Participants were tested on all 216 studied objects. Retrieval was divided into three blocks, each consisting of 72 trials. For each trial, participants were presented with an object in the center of the screen. While the object was presented on the screen, they were asked to decide the category of the associate the object was most recently paired with (i.e., in the fourth block of encoding). Each trial was followed by the arrow task lasting 2–6 sec. Each block was pseudorandomized so the participants were not presented with more than three trials of the same condition (i.e., high interference, low interference, and no interference) in a row. Each block lasted 9 min, for a total of 21 min.

Post-retrieval

After exiting the scanner and completing MoCA, participants began the post-retrieval phase. Participants were again tested on all 216 studied objects. The post-retrieval test was given to assess the specificity of the participants' memories of the pairings. Again, this task was divided into three blocks, with each block consisting of 72 trials. For each trial, participants were asked three questions.

First, they were asked again to decide which associate category (i.e., face or scene) the object was most recently paired with (i.e., in the fourth block of encoding). Second, they were asked what specific category the object was last paired with. If the participant responded with "Face" for the first question, we then asked them to respond with whether it was a male or female face. If they responded with "Scene," we asked them to respond with whether it was an indoor or outdoor scene. Third, they were asked what specific associate the object was last paired with. For example, if the participant responded with "Male," we then presented them with the four male faces they were shown throughout encoding and asked them to pick the specific one. Participants were given the response options for each follow-up question based on their previous response regardless of whether or not their previous response was correct, making the participants unaware of their accuracy of the task. For example, if the correct answer was "Face" but the participant responded with "Scene," they were then asked if the object was most recently paired with an indoor or outdoor scene. Each question was presented on the screen for 3 sec; however, if the participant responded before 3 sec and after 1 sec, they were prompted with the next question. Thus, post-retrieval was semi-self-paced.

fMRI Preprocessing

Scanning was performed on a 3-T Siemens TIM Trio system at the Center for Advanced Brain Imaging. Functional data were acquired using a gradient echo pulse sequence (37 transverse slices oriented along the anterior–posterior commissural axis with a 30° upward tilt to avoid the eyes, a repetition time of 2 sec, an echo time of 30 msec, $3 \times 3 \times 3.5$ mm voxels, a 0.8-mm interslice gap). Three encoding and three retrieval blocks of 284 volumes each were acquired. The first two volumes of each block were discarded to allow for equilibration effects. A high-resolution T1-weighted magnetization prepared rapid gradient echo image was collected for normalization.

fMRI Analyses

Data were analyzed via SPM12 (SPM12, www.fil.ion.ucl.ac.uk/spm/software/spm12/). Images were corrected for differences in slice timing acquisition using the middle slice of each volume as the reference, spatially realigned and resliced with respect to the first volume of the first block. Each participant's magnetization prepared rapid gradient echo scan was coregistered to the mean EPI image, produced from spatial realignment. Each coregistered structural scan was then segmented using the Diffeomorphic Anatomical Registration Through Exponentiated Lie Algebra SPM12 toolbox (Ashburner, 2007). The gray and white matter segmented images were used to create a study-specific template using the Diffeomorphic Anatomical Registration Through

Exponentiated Lie Algebra toolbox, and the flow fields containing the deformation parameters to this template for each participant were used to normalize each participant's realigned and resliced EPIs to Montreal Neurological Institute space. Normalized EPI images were written to $3 \times 3 \times 3$ mm and smoothed with an 8-mm FWHM isotropic Gaussian kernel. The EPI data were then high-pass filtered to a minimum of 1/128 Hz and grand mean scaled to 100.

Statistical analysis was performed in two stages. First, neural activity was modeled as a series of 0-sec epochs at study (i.e., delta functions) of the various event types (e.g., high interference correct, high interference incorrect) and convolved with a canonical hemodynamic response function. The time courses were then down-sampled to the middle slice to form the covariates for the general linear model. For each participant and block, six covariates representing residual movement-related artifacts, determined by the spatial realignment step, were included in the first-level model to capture residual (linear) movement artifacts. Voxel-wise parameter estimates for these covariates were obtained by restricted maximum likelihood estimation, using a temporal high-pass filter (cutoff = 128 sec) to remove low-frequency drifts and modeling temporal autocorrelation across scans with an AR(1) process. Contrasts of the parameter estimates for each participant were submitted to the second stage of analysis (treating participants as a random effect). A mixed ANOVA model was created separately for the encoding and retrieval periods that allowed us to examine both within-group effects and group interactions. For each period, a 5×2 model included factors of Trial type (high interference correct, high interference incorrect, low interference correct, low interference incorrect, no interference correct) and Age group (young, old). Correct trials were trials in which the participant correctly identified the target category at both retrieval and post-retrieval. To have enough trials to compare correct to incorrect trials, our incorrect trials were composed of the trials in which the participant incorrectly identified the target category at both retrieval and post-retrieval together with responses in which the participant changed their responses between retrieval and post-retrieval. We did this under the premise that, if the participants did change their response, they did not have a strong memory trace for that object–associate pairing (see Behavioral Results for confirmation). Most participants had too few incorrect responses for the no-interference condition, and so this condition was not included in the analysis. Importantly, this ANOVA model allowed us to not only assess interference effects but also determine whether regions sensitive to interference are also sensitive to accuracy.

Covariates modeling the mean across conditions for each participant were also added to each model for all contrasts in the second-level model to remove between-participant variance of no interest, as per the optimal event-related fMRI suggestions in Chapter 10 of the SPM manual

(SMP12; www.fil.ion.ucl.ac.uk/spm/doc/manual.pdf). A weighted least squares estimation procedure was used to correct for inhomogeneity of covariance across within-group conditions and inhomogeneity of variance across groups.

To determine the parameters for multiple comparison corrections, we used FMRISTAT (www.math.mcgill.ca/keith/fmri-stat/) to acquire the cluster extent and t value threshold for voxel-level statistics. All results were thresholded at $p < .001$ with a cluster extent of 17, which yielded whole-brain results corrected for multiple comparisons at $p < .05$. We derived this threshold via Monte Carlo simulations to correct for Type I and II errors (Slotnick, Moo, Segal, & Hart, 2003).[1] Furthermore, all effects were confirmed via inclusive masking ($p < .01$) with each side of the effect (i.e., young and older adult effects) to elucidate the source of interactions in a given contrast (e.g., young > old: high interference correct > high interference incorrect), allowing us to determine whether an effect was driven by a group crossover or whether an effect was in fact larger in one group than another, as well as to ensure that main effects across groups were reliable for each group. For common effects, across groups, contrasts were masked exclusively with the SPMs for the interactions between these factors using a liberal uncorrected threshold of $p < .05$ for the masks to restrict memory effects to those "common" (i.e., similar size) across groups/conditions.

RESULTS

For all behavioral analyses, significant interactions at an alpha (α) level of .05 were followed up with subsidiary ANOVAs and t tests to determine the source of the effects. Where appropriate, reported p values were corrected using Huynh–Feldt corrections.

Behavioral Results

General Associative Memory Accuracy

To assess interference and/or age differences for general associative memory, we calculated general memory accuracy as the percentage of responses in which the participant correctly identified the target category at both retrieval and post-retrieval. This was under the premise that, if the participants did change their response, they did not have a strong memory trace for that object–associate pairing, as confirmed in our analyses below. As participants had to identify either face or scene as the general target category twice, chance is equal to 25%. These percentages are displayed in Figure 2.

A 3 Interference (high interference, low interference, no interference) × 2 Age (young, old) ANOVA on these percentages revealed a main effect of Interference, $F(2, 96) = 42.229$, $p < .001$, $\eta_p^2 = .468$, but no main effect of Age, $F(1, 48) < 1$, $p = .651$, $\eta_p^2 = .004$, nor an interaction, $F(2, 96) < 1$, $p = .574$, $\eta_p^2 = .011$. As predicted, both young and older adults remembered more no interference than high, $t(49) = 8.332$, $p < .001$, and low, $t(49) = 3.616$, $p = .001$, interference associations and more low interference than high interference associations, $t(49) = 5.939$, $p < .001$. Data were also examined by estimating a Bayes factor using Bayesian information criteria (Wagenmakers, 2007). As we were mostly interested in any effect of age, we only calculated Bayes factor for any nonsignificant main effects or interactions involving Age in this analysis and all other reported analyses. An estimated Bayes factor (alternative/null) for the main effect of Age suggested that data were 0.399 times more likely to occur under the alternative than the null and were 0.169 times more likely for the Interference × Age interaction.

Specific Associative Memory Accuracy

We next wanted to assess how proactive interference and/or age affected memory for the specific details of the associations. We did this by calculating the percentage of responses in which the participant correctly chose the specific target associate (i.e., if the object was paired with a male face and the participant chose face at retrieval and at post-retrieval, then male and then the correct male face; Accuracy = [specific target associate correct response count/retrieval hits]). As participants were required to decide between two options for the general target category question at both retrieval and post-retrieval, then decide between two options for the specific category

Figure 2. The mean percentage of correct responses for target category separated by interference condition, for young and older adults. Error bars represent the *SEM*.
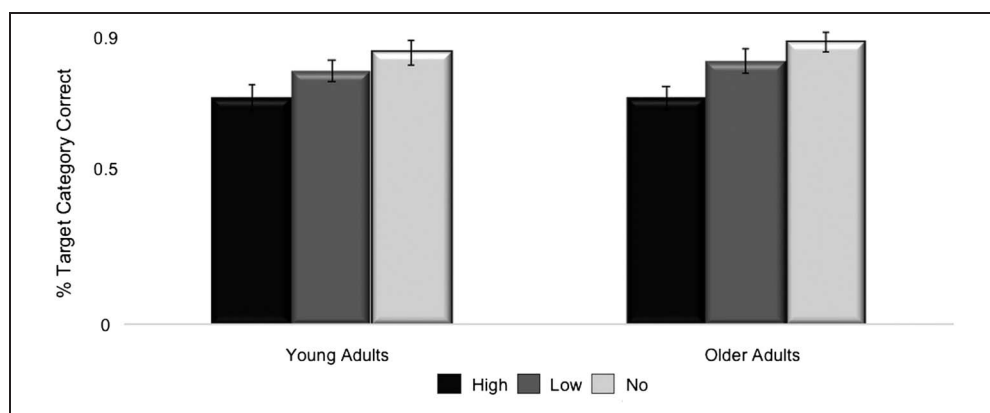
Figure 3. The mean percentage of correct responses for the specific target associate separated by interference condition, for young and older adults. Error bars represent the *SEM*.
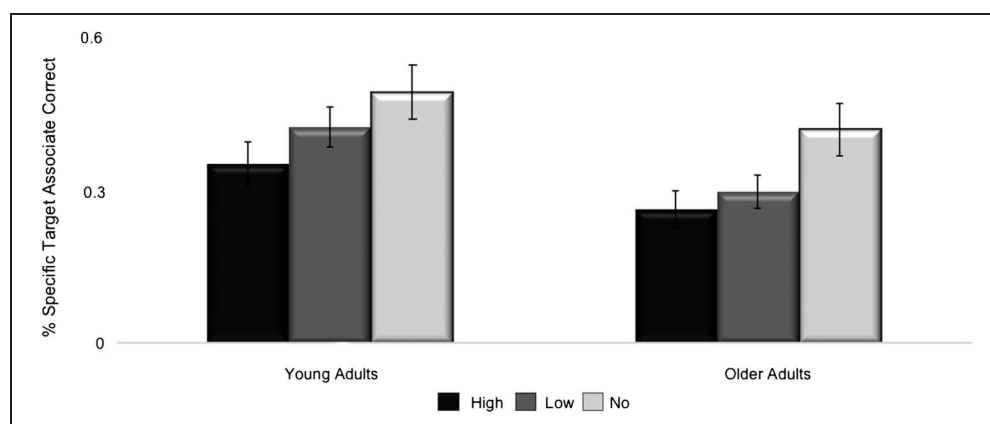
question at post-retrieval, and finally decide between four options for the specific associate question at post-retrieval, chance is equal to 10%. These percentages are displayed in Figure 3.

A 3 Interference (high interference, low interference, no interference) × 2 Age (young, older) ANOVA on these percentages revealed a main effect of Interference, $F(2, 96) = 47.612, p < .001, \eta_p^2 = .498$, and a marginal main effect of Age, $F(1, 48) = 3.265, p = .077, \eta_p^2 = .064$, but no interaction, $F(2, 96) = 1.553, p = .217, \eta_p^2 = .031$. As predicted, both young and older adults remembered more no interference than high, $t(49) = 9.498, p < .001$, and low, $t(49) = 5.551, p < .001$, interference associations and more low interference than high interference associations, $t(49) = 3.919, p < .001$. An estimated Bayes factor (alternative/ null) for the main effect of Age suggested that data were 1.210 times more likely to occur under the alternative than the null and 0.718 times more likely for the Interference × Age interaction.

Changed Target Category Responses between Retrieval and Post-retrieval

Although memory accuracy between retrieval and post-retrieval was highly correlated across age, $r(48) = .763$,

$p < .001$, we were interested in how often the participants changed their target category response and if this differed as a function of interference or age. We calculated this as (% changed target category response at retrieval and post-retrieval / all responses at retrieval). These percentages are presented in Figure 4.

A 3 Interference (high interference, low interference, no interference) × 2 Age (young, older) ANOVA on these percentages revealed a revealed a main effect of Interference, $F(2, 96) = 29.686, p < .001, \eta_p^2 = .382$, but no main effect of Age, $F(1, 48) < 1, p = .793, \eta_p^2 = .001$, or interaction, $F(2, 96) < 1, p = .979, \eta_p^2 < .001$. As predicted, both young and older adults changed their response less for no interference than high, $t(49) = 7.561, p < .001$, and low, $t(49) = 3.980, p < .001$, interference associations and less for low interference than high interference associations, $t(49) = 3.932, p < .001$.

RTs

We investigated how RTs differed as a function of interference, memory performance, and age for both encoding and retrieval responses. These data are presented in Table 2.

To account for any multiplicative slowing effects between age and the other conditions, we performed a

Figure 4. The mean percentage of changed target category response, regardless of accuracy, between retrieval and post-retrieval separated by interference condition, for young and older adults. Error bars represent the *SEM*.
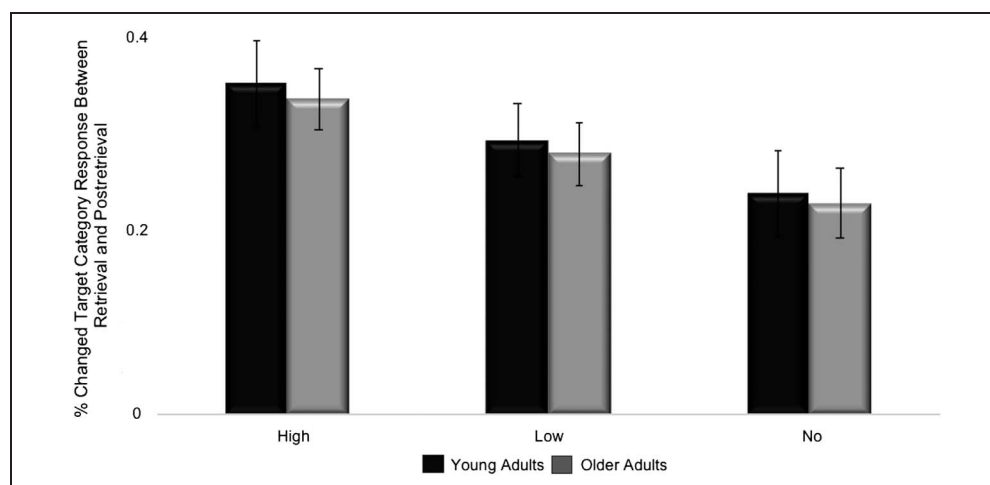
Table 2. RTs at Encoding and Retrieval

	High		Low		No	
	Correct	*Incorrect*	*Correct*	*Incorrect*	*Correct*	*Incorrect*
Encoding						
Young adults	1.34 (0.184)	1.34 (0.24)	1.29 (0.18)	1.31 (0.23)	1.23 (0.18)	1.26 (0.26)
Older adults	1.48 (0.25)	1.47 (0.26)	1.39 (0.22)	1.45 (0.21)	1.38 (0.25)	1.39 (0.25)
Retrieval						
Young adults	1.46 (0.23)	1.61 (0.21)	1.41 (0.23)	1.58 (0.21)	1.37 (0.17)	1.54 (0.25)
Older adults	1.63 (0.22)	1.75 (0.22)	1.56 (0.22)	1.81 (0.24)	1.53 (0.17)	1.75 (0.29)

RTs are in seconds. Standard deviations are in parentheses.

log transformation on the RTs before statistical analyses (Faust, Balota, Spieler, & Ferraro, 1999). For encoding RTs, an Interference (high, low, no) × Memory (target category correct, target category incorrect) × Age ANOVA revealed a main effect of Interference, $F(2, 96) = 6.019, p = .004, \eta_p^2 = .111$; a marginal main effect of Memory, $F(1, 48) = 3.488, p = .068, \eta_p^2 = .068$; no main effect of Age, $F(1, 48) = 2.330, p = .133, \eta_p^2 = .046$; no Interference × Age interaction, $F(2, 96) < 1, p = .410, \eta_p^2 = .018$; no Memory × Age interaction, $F(1, 48) < 1, p = .543, \eta_p^2 = .008$; no Interference × Memory interaction, $F(2, 96) < 1, p = .997, \eta_p^2 < .001$; and no Interference × Memory × Age interaction, $F(2, 96) < 1, p = .635, \eta_p^2 = .009$. Both young and older adults responded more slowly to subsequently incorrect than correct trials. Follow-up *t* tests revealed that both young and older adults responded faster to no interference than high, $t(49) = 3.292, p = .002$, and low, $t(49) = 2.111, p = .040$, interference associations but responded similarly to low interference and high interference associations, $t(49) = 1.249, p = .218$. An estimated Bayes factor (alternative/null) for the main effect of Age suggested that data were 1.577 times more likely to occur under the alternative than the null, 0.150 times more likely for the Interference × Age interaction, and 0.194 times more likely for the Memory × Age interaction.

For retrieval RTs, an Interference (high, low, no) × Memory (target category correct, target category incorrect) × Age ANOVA revealed a main effect of Interference, $F(2, 96) = 3.912, p = .025, \eta_p^2 = .075$; a marginal main effect of Age, $F(1, 48) = 3.025, p = .088, \eta_p^2 = .059$; no main effect of Memory, $F(1, 48) < 1, p = .726, \eta_p^2 = .003$; no Interference × Age interaction, $F(2, 96) < 1, p = .691, \eta_p^2 = .007$; no Memory × Age interaction, $F(1, 48) = 1.744, p = .193, \eta_p^2 = .035$; no Interference × Memory interaction, $F(2, 96) < 1, p = .532, \eta_p^2 = .013$; and no Interference × Memory × Age interaction, $F(2, 96) = 1.216, p = .301, \eta_p^2 = .025$. At encoding, RTs were modulated by interference with young and older adults responding slower to high interference than no interference,

$t(49) = 2.482, p = .017$, and low interference, $t(49) = 2.033, p = .047$, associations. RTs were similar for low interference and no interference associations, $t(49) = 1.072, p = .289$. An estimated Bayes factor (alternative/null) for the main effect of Age suggested that data were 1.162 times more likely to occur under the alternative than the null, 1.470 times more likely for the Interference × Age interaction, and 0.302 times more likely for the Memory × Age interaction.

We wanted to mention that one may be thinking that the interference effects we found could be because of pairing the face and scene associates with multiple objects. We did attempt pairing trial unique faces and scenes with the objects in an earlier version of the task, but older adults, and many young participants, performed near chance for their memory decisions. In the end, we determined that using eight faces and eight scenes and equating the number of objects each face and scene was paired with (an average of 13 times) was best. Although it is true that there could be some interference by pairing a face or scene associate with multiple objects, we do not believe that to be the sole cause of interference. If it was, we would not see the difference between interference conditions, as the faces and scenes were paired with high, low, and no interference items an equal number of times.

fMRI Results

Encoding

Before we discuss our results, we wanted to give a reminder that, for our imaging contrasts, correct trials were trials in which the participant correctly identified the target category at both retrieval and post-retrieval. Incorrect trials were composed of the trials in which the participant incorrectly identified the target category at both retrieval and post-retrieval together with responses in which the participant changed their responses between retrieval and post-retrieval. At encoding, the VLPFC, as seen in

Figure 5. Interference effects at encoding for the left VLPFC for the High/Low Interference > No Interference contrast. Plots show parameter estimates for high-interference correct and incorrect trials, low-interference correct and incorrect trials, and no-interference correct trials. Error bars represent the *SEM*. Exclusive masking conducted as described in the fMRI Analyses section.

Encoding Interference Effects
High/Low > No
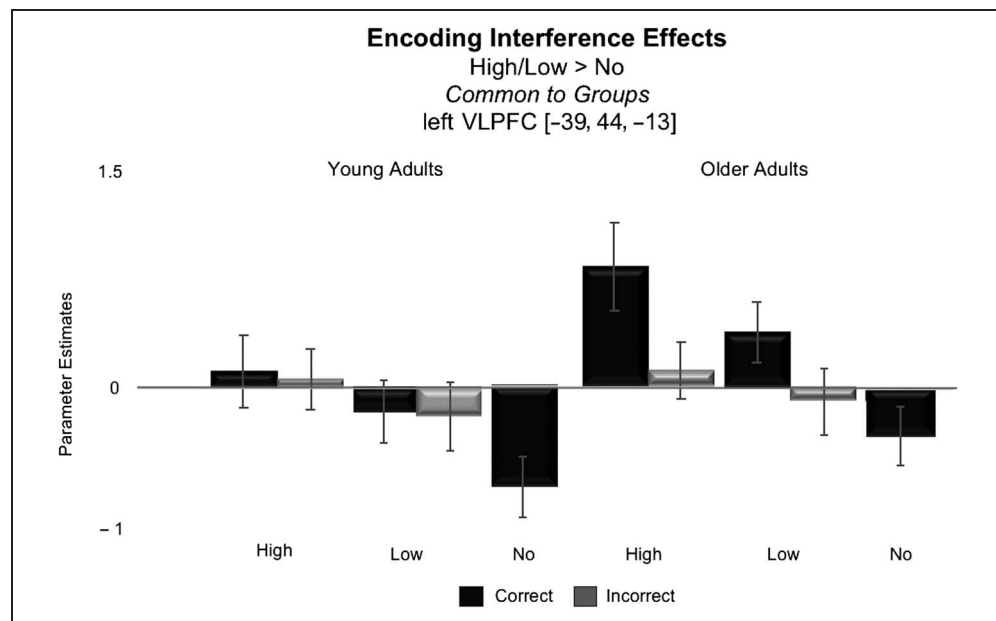*Common to Groups*
left VLPFC [−39, 44, −13]

Figure 5, and the fusiform gyrus were sensitive to interference. No regions distinguished high and low interference, correct from incorrect trials, or age groups. These regions are presented in Table 3. Because of our predictions about the DLPFC being sensitive to memory accuracy, we reduced the voxel-level threshold to $p = .005$. Even at this substantially reduced threshold, there were no significant voxels in the DLPFC that were sensitive to accuracy.

Retrieval

During retrieval, and in contrast to encoding, no regions were sensitive to interference. By contrast, several regions were sensitive to associative memory accuracy, including the ventromedial pFC (vmPFC), as seen in Figure 6; the supramarginal gyrus; and the visual association cortex. These regions are presented in Table 4. Because of our predictions about the left VLPFC and

DLPFC, we reduced the voxel-level threshold to $p = .005$. Even at this substantially reduced threshold, there were no significant voxels in the left VLPFC or DLPFC that were sensitive to interference or accuracy. We did observe a cluster in the right hippocampus, [30, −13, −13], t score = 3.45, cluster size = 28, that was sensitive to associative memory accuracy, across interference conditions and age groups (high/low correct > incorrect).

In Figure 6, it appears as though young adults show no difference in vmPFC activity between correct and incorrect low-interference trials, whereas older adults do. To explore this possibility, we extracted mean parameter estimate values from this vmPFC coordinate and entered them into an Interference (high interference, low interference) × Memory (correct, incorrect) × Age (young, older) ANOVA. This ANOVA revealed a main effect of Memory, $F(1, 48) = 19.941$, $p < .001$, $\eta_p^2 = .289$; a marginal Interference × Age interaction, $F(1, 48) = 3.748$, $p = .059$, $\eta_p^2 = .072$; an Interference × Memory × Age

Table 3. Peak Coordinates for the Whole-Brain Analysis of the Encoding Task

Region	L/R	BA	x, y, z	t Score	p Value	Cluster Size
Across age: high > no						
VLPFC	L	45/47	−33, 35, −13	4.13	.001	19
Fusiform gyrus	L	37	−48, −55, −10	3.97	.001	24
Across age: high/low > no						
VLPFC	R	47	36, 38, −10	4.12	.001	21
VLPFC	L	47	−39, 44, −13	3.76	.001	25

The reported p value is the peak-level uncorrected p value. L = left; R = right.

Figure 6. Accuracy effects at retrieval for the right vmPFC. Plots show parameter estimates for high-interference correct and incorrect trials, low-interference correct and incorrect trials, and no-interference correct trials. Error bars represent the *SEM*. Exclusive masking conducted as described in the fMRI Analyses section.

Retrieval Accuracy Effects
High/Low Correct > Incorrect
Common to Groups
right vmPFC [6, 23, −7]
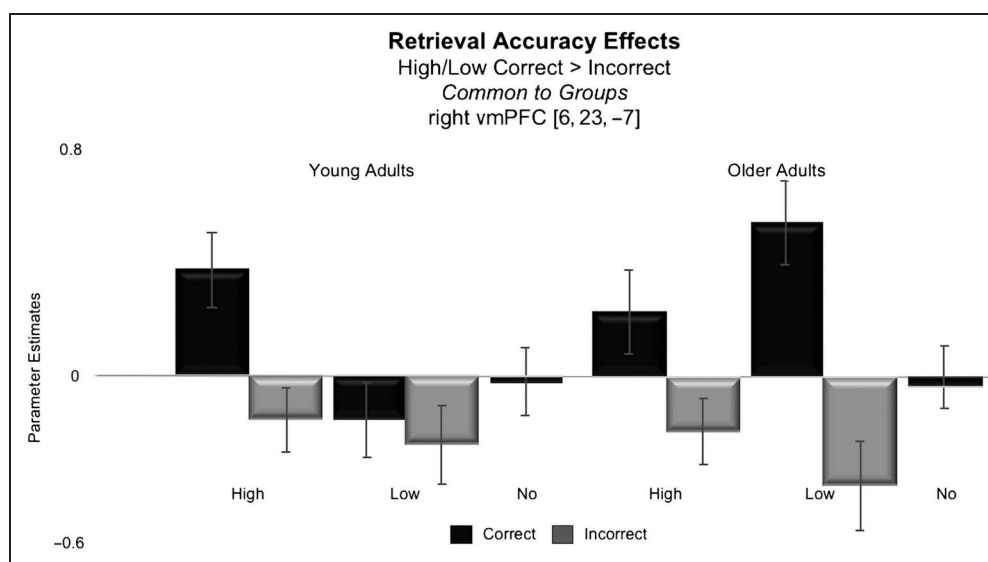
interaction, $F(1, 48) = 6.515$, $p = .014$, $\eta_p^2 = .120$; no main effect of Interference, $F(1, 48) = 1.693$, $p = .199$, $\eta_p^2 = .034$; no main effect of Age, $F(1, 48) < 1$, $p = .630$, $\eta_p^2 = .005$; no Memory × Age interaction, $F(1, 48) = 2.759$, $p = .103$, $\eta_p^2 = .054$; and no Interference × Memory interaction, $F(1, 48) < 1$, $p = .864$, $\eta_p^2 = .001$. Consistent with our analysis above, both young and older adults recruited the vmPFC more for correct than incorrect trials. As can be seen in Figure 6, young adults recruited the vmPFC more for high interference correct than incorrect trials, $t(24) = 2.858$, $p = .009$, but similarly for low interference correct and incorrect trials, $t(24) = 0.420$, $p = .678$. Older adults recruited the vmPFC more for high interference correct than incorrect trials, $t(24) = 2.117$, $p = .045$, and more for low interference correct than incorrect trials, $t(24) = 4.123$, $p < .001$.

DISCUSSION

The current study investigated if age-related deficits in pFC-mediated cognitive control processes underlie age-related differences in the resolution of proactive interference in an associative memory task. As predicted, memory for both the general target category and the specific target associate worsened as the level of proactive interference increased, with no robust age differences. The left VLPFC was sensitive to the level of interference but not the successful resolution of interference for both young and older adults at encoding. Interestingly, the vmPFC, but not the DLPFC, was sensitive to the successful resolution of interference at retrieval. Young adults recruited the vmPFC more during correct than incorrect high-interference trials but not more during correct than incorrect low-interference trials. Older adults, on the other hand, recruited the vmPFC more for correct than incorrect for both high- and low-interference trials. These results and their implications are discussed below.

Older Adults Are Not Disproportionately Susceptible to Proactive Interference

With our new design that was aimed to increase the reliance on recollection, we still see that older adults are not disproportionately susceptible to proactive interference in associative memory. This was evident in both memory accuracy and RTs. Consistent with previous studies, RTs at both encoding and retrieval increased as the level of interference increased (for a review, see Jonides & Nee, 2006). At encoding, this suggests that young and older adults are sensitive to interference and perhaps were engaging in more effortful encoding of the target–object

Table 4. Peak Coordinates for the Whole-Brain Analysis of the Retrieval Task

Region	L/R	BA	x, y, z	t Score	p Value	Cluster Size
Across age: high/low correct > high/low incorrect						
vmPFC	R	11	6, 23, −7	4.36	.001	212
Visual association cortex	L	18	−12, −91, −10	3.83	.001	25
Supramarginal gyrus	L	40	−66, −34, 23	3.72	.001	26

The reported *p* value is the peak-level uncorrected *p* value.

pair, as the high/low-interference objects had been paired with lures. At retrieval, this suggests that young and older adults were responding slower to the higher interference trials because they were engaging in processes to resolve the interference.

For both young and older adults, associative memory accuracy for the general target category worsened as the level of interference increased. This suggests that, when interference from the lure associate is high, the ability to successfully retrieve even general details about the target associate is impaired. Although we modified the retrieval task to rely less on familiarity by presenting participants with the category labels rather than images of the associates, it is possible that these general memory decisions are at least somewhat supported by familiarity. Previous studies have found that memory for general details is dependent on familiarity (for a review, see Yonelinas, 2002), rather than recollection and that older adults are able to perform equally as well as young adults on tasks that rely on familiarity (Light et al., 2000). Thus, our lack of an age difference in memory for the general target category could be because of the reliance on familiarity, as we found in our prior study (Dulas & Duarte, 2016).

In our post-retrieval task, which was designed to require more recollection-based decisions compared to our retrieval task, we did not see robust age effects. Young and older adults' associative memory accuracy for the specific target associate similarly worsened as the level of interference increased. One aspect of our design that may have attenuated any disproportionate susceptibility to proactive interference in our older adults is the implementation of an effective encoding strategy. Specifically, participants were asked to use interactive imagery to encode associations between objects and their paired faces or scenes (e.g., "imagine this woman eating this grapefruit"). Previous studies have found that age-related associative memory deficits are reduced when older adults are given effective encoding strategies that they typically fail to self-initiate (Glisky & Kong, 2008; Naveh-Benjamin, Brav, & Levy, 2007; Glisky, Rubin, & Davidson, 2001; Hay & Jacoby, 1999).

Evidence for susceptibility to proactive interference for both age groups is further corroborated by our finding that interference has an effect on the number of changed responses between retrieval and post-retrieval similarly for young and older adults. In addition, using the Kass and Raftery (1995) rule of thumb, each of our Bayes factor estimates for effects and interactions with Age provided, at best, negligible evidence (a Bayes factor of 1–3) in favor of the alternative hypothesis, suggesting we are more likely to not find any age differences than we are to find any age differences. Collectively, these results suggest that older adults have somewhat greater difficulty remembering specific associations between objects and paired faces or scenes but are not disproportionately susceptible to proactive interference. This is in line with previous studies (Dulas & Duarte, 2016; Guez & Naveh-Benjamin, 2016)

but stands in contrast to others that have found older adults are disproportionately susceptible to proactive interference in associative memory (Burton et al., 2019; Ebert & Anderson, 2009; Jacoby et al., 2005). These mixed results could be attributed to few different possibilities. A non-mutually exclusive possibility may be related to the pictorial stimulus materials we used. Whereas most prior studies have assessed associative memory for word pairs, we used object–face and object–scene pairings. Although a direct comparison with word pairs would be needed to test this hypothesis, memory in the current study was likely supported by the processes underlying the "picture superiority effect" in which pictures are better remembered than other stimuli, an effect that is both observed in associative memory tasks (Hockley, 2008) and preserved with age (Winograd, Smith, & Simon, 1982). It has been suggested that faster activation of semantic associations for pictures than words may allow for more time to generate robust, meaningful associations between stimuli (Hockley & Bancroft, 2011).

More in the realm of task design, one possibility, discussed already, is that older adults were able to successfully overcome proactive interference in the current study because of our engaging encoding task. The studies that showed older adults were disproportionally susceptible to proactive interference employed intentional encoding instructions only. As discussed above, previous studies have found that age-related associative memory deficits are reduced when older adults are given effective encoding strategies that they typically fail to self-initiate in less engaging tasks (Glisky & Kong, 2008; Naveh-Benjamin et al., 2007; Glisky et al., 2001; Hay & Jacoby, 1999). Another possibility is that any increased susceptibility to proactive interference in older adults may have been attenuated by administering a recognition rather than a cued recall task. Again, the studies that showed older adults were disproportionally susceptible to proactive interference administered a cued recall task. Previous studies have found that age differences in associative memory performance are reduced when older adults are given a recognition task compared to a cued recall task, as reported in this meta-analysis (Rhodes, Greene, & Naveh-Benjamin, 2019).

In addition, it is also possible that these mixed results in the literature are because of the samples of young and older adults used in each study. It is possible that some older adults are able to engage the cognitive control processes necessary to resolve proactive interference to the same level that young adults do. The older adults in the current study had minimal medical issues and, on average, a bachelor's degree. The previous studies that found that older adults were disproportionally susceptible to proactive interference had older adult samples similar to ours in age range and years of education; however, these studies were not fMRI studies, which likely lessened their sampling bias (Burton et al., 2019; Ebert & Anderson, 2009; Jacoby et al., 2005). Health problems

and functional limitations, such as high blood pressure, diabetes, history of heart attack, and strokes, make participants ineligible for fMRI, leading researchers to typically study the "healthiest" of older adults who do not often represent the general population of the elderly (Dotson & Duarte, 2020). Given the extensive research on the negative impact health-related issues have on cognition (for a review, see Stern & Carstensen, 2000), it is conceivable that older adults who participate in fMRI studies represent a "super aging" sample with fewer cognitive difficulties than older adults in other cognitive studies. Unfortunately, little to no research has been conducted to compare performance across participant samples in imaging and behavioral-only studies. Future research should compare the cognitive abilities of older adults eligible for fMRI studies with those who are ineligible to shed light on the extent these sampling biases have on cognitive abilities.

We would like to note that, in the current study, memory accuracy could be impacted by the level of mnemonic interference from the lure associate that varied across conditions and/or difficulty remembering which of the associates was more recently paired with the object. We believe the lower memory accuracy for high- than low-interference conditions, despite similar recency discrimination demands, and the slower RTs for target encoding trials after lure encoding are difficult to explain solely from a recency discrimination account and more easily explained by a mnemonic interference account that incorporates recency as mechanism that has to be overcome to resolve interference. Similarly, we believe this to be the case for memory strength as well. In this task, it is likely that, to correctly remember which associate a high-interference object was paired with, the participants needed to overcome memory strength from the lure (i.e., the lure was paired with the object just as many times as the target) and recency (i.e., the lure was recently paired with the object).

Older and Younger Adults Are Equally Able to Engage pFC-mediated Control Processes to Resolve Proactive Interference: Evidence for CRUNCH

Consistent with previous studies, the left VLPFC was sensitive to the level of interference but not accuracy (Atkins & Reuter-Lorenz, 2011; Öztekin et al., 2009). For both young and older adults, the left VLPFC was recruited more for high- and low-interference trials than no-interference trials at encoding. The left VLPFC has been implicated in post-retrieval selection (Badre, Poldrack, Paré-Blagoev, Insler, & Wagner, 2005; for a review, see Oren et al., 2017; Barredo, Öztekin, & Badre, 2015; Badre & Wagner, 2007; Dobbins et al., 2003), a process that is engaged when multiple competing representations are activated and relevant information needs to be enhanced whereas irrelevant information needs to be

suppressed. However, the left-VLPFC cluster we found was more anterior (BA 47) than the left-VLPFC clusters typically implicated in post-retrieval selection (BA 45). The left-anterior VLPFC has been implicated in controlled retrieval of conceptual representations. This controlled retrieval process is thought to specify and/or refine cues used to probe memory, which results in the retrieval of episodic details from goal-relevant domains (for a review, see Badre & Wagner, 2007). In this vein, it seems possible that participants may be reactivating the memory of the old lure associate during encoding of new (target) associations, in such a way as to update their memory with the relevant target–object pairing.

Similarly, the left-anterior pFC has also been indicated in maintaining memory-relevant goals during encoding (for a review, see Mitchell & Johnson, 2009). It is also possible that our observed pFC activity represents a process in which participants are differentiating the first three blocks of the object–associate pairings, from the fourth block of the target–associate pairing, in a way to engage in deeper encoding of this pairing. This account would be consistent with the strategic–encoding account proposed by Sahakyan and Delaney (2003) in their directed-forgetting tasks. In these tasks, participants are presented two lists of items, instructed to either forget or remember the first list before being presented with the second list, and then tested on their memory for both lists. After each list presentation, participants were asked about their encoding strategy, and these strategies were grouped as either shallow, deep, or intermediate. They found that more participants switched from shallow to deep encoding between List 1 and List 2 if they were instructed to forget rather than remember List 1. They posit that this could be because of two possibilities: Either participants realized a shallow encoding process was not the most effective process, or participants were trying to differentiate the lists for later test by using different strategies. In this vein, it is possible that participants in the current study were engaging in deeper encoding for high/low-interference than no-interference items during the fourth block of encoding in an effort to separate these target–object pairings from the previous associate–object pairings in the first three blocks in an effort to support later memory. The context change between the first three blocks, which were administered in a behavioral testing room, and the fourth block, which was administered in the fMRI scanner, may have allowed participants to separate these events, which resulted in them employing a left-anterior VLPFC memory goal-relevant encoding process during that fourth encoding block. Regardless of which account is taken, our lack of finding an age-related difference in the recruitment of the left VLPFC is consistent with our behavioral findings that older adults were not disproportionally susceptible to proactive interference. These data support the idea that, when older adults are provided environment support, in the form of effective encoding instructions, differences in at least some

pFC recruitment may be attenuated (Logan, Sanders, Snyder, Morris, & Buckner, 2002).

Interestingly, we did not find evidence that the left VLPFC was sensitive to interference nor that the DLPFC was sensitive to accuracy at retrieval. This is inconsistent with our previous study (Dulas & Duarte, 2016) as well as a number of other studies (for a review, see Atkins & Reuter-Lorenz, 2011; Öztekin et al., 2009; Badre & Wagner, 2007) who have found the left VLPFC and the DLPFC to be sensitive to interference and memory accuracy, respectively, at retrieval. One possibility for this discrepancy is that, by modifying our retrieval task to present participants with the category labels rather than presenting them with images of target and lure stimuli, as these other studies have done (for a review, see Dulas & Duarte, 2016; Atkins & Reuter-Lorenz, 2011; Öztekin et al., 2009; Badre & Wagner, 2007), we reduced the demand on these pFC-mediated cognitive control processes. Previous neuroimaging studies have indicated that the lateral pFC is more involved in control of perceptual-driven information, whereas the medial pFC is more involved in control of self-generated information (for a review, see Mitchell & Johnson, 2009). From this perspective, it is probable that, in these other studies, participants recruited left-VLPFC post-retrieval selection to inhibit the lure and enhance the target because they were presented with target and lure stimuli, whereas, in the current study, participants were not presented with any images but likely imagined some representation of the target–object associations they previously encoded.

Similarly, we may not have found any evidence of DLPFC-mediated post-retrieval monitoring because our retrieval task put less of a demand on perception-based monitoring and more of a demand on the self-generated monitoring. Indeed, we found the vmPFC, which has been implicated in the monitoring of internally generated, imagined information in source memory tasks (for a review, see Mitchell & Johnson, 2009), was sensitive to memory accuracy at retrieval for both young and older adults. It was recruited more for high/low-interference correct target category trials than high/low-interference incorrect target category trials, likely indicating the monitoring of the successful retrieval of the target–object associative context the participants self-generated at encoding. For young adults, the vmPFC was recruited more for correct than incorrect high-interference trials but similarly recruited for correct and incorrect low-interference trials. Whereas, for older adults, the vmPFC was recruited more for correct than incorrect for both high- and low-interference trials, with no difference between high- and low-interference conditions. Given the lack of any age differences in low-interference memory performance, the difference in vmPFC activity for low-interference correct and incorrect trials for older but not young adults likely could reflect a compensatory process. Specifically, demands on monitoring of recovered associations and vmPFC recruitment may have been greater for older than young adults at a lower level of proactive interference for older adults to show matched memory performance. This is in line with the Compensation-Related Utilization of Neural Circuits Hypothesis (CRUNCH), which posits that older adults recruit cognitive control operations, and supporting pFC activity, more than young adults to compensate for cognitive decline (Reuter-Lorenz & Cappell, 2008; Reuter-Lorenz & Lustig, 2005). According to this theory, older adults reach their task capacity sooner than young adults such that overrecruitment of regions that support cognitive control operations and matched performance is typically seen at lower levels of task difficulty. The pattern observed here for the vmPFC is perfectly consistent with this theory.

In addition, it is important to mention that, although hippocampal activity was not observed at our cluster-adjusted threshold, when we lowered our threshold, we observed a cluster in the right hippocampus. This activity was insensitive to interference or age. Consistent with prior studies (de Chastelaine et al., 2015, 2016; Angel et al., 2013; Rugg & Morcom, 2005) as well as our previous study (Dulas & Duarte, 2016), when memory performance is roughly matched between age groups, older adults recruit the MTL "core episodic network" to the same degree as the young adults. This, together with the results discussed above, points to pFC dysfunction as a primary contributor to age-related cognitive, including associative memory, impairments (Duarte & Dulas, in press).

Conclusion

This study found that older adults are not disproportionally susceptible to proactive interference in associative memory. Older adults engaged in more right vmPFC monitoring than young adults to support their successful associative retrieval at lower levels of proactive interference but were able to spontaneously engage in left-VLPFC controlled retrieval to the same extent as young adults during new associative learning. Collectively, these results suggest that older adults are able to engage in pFC-mediated cognitive control processes necessary to successfully resolve proactive interference in associative memory to the same level as young adults.

Acknowledgments

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Note

1.   Our *XYZ* matrix dimensions were 68 × 68 × 37, with a 3 × 3 × 3.5 mm voxel size resampled to 3 × 3 × 3 mm. The Gaussian FWHM was set to 15, which was the most conservative (highest) value computed using the *t* statistic maps associated with the contrasts of interest. Furthermore, 1000 simulations were run.

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