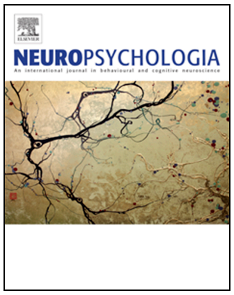

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Effects of age on the neural correlates of encoding source and item information: an fMRI study

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Abstract

The effects of age on encoding-related neural activity predictive of accurate item and source memory judgments were examined with fMRI, with an a priori focus of the inferior frontal gyrus (IFG) and hippocampus. During a scanned study phase, young and older adults viewed a series of pictures of objects and made one of two judgments on each object. At test, which occurred outside of the scanner, an 'old/new' judgment on each test item was followed, for those items endorsed old, by a source judgment querying the study task. Neural activity predictive of accurate subsequent item and source memory judgments was identified in bilateral IFG, several other cortical regions and bilateral hippocampus. Cortical effects were graded in the young group (source > item > miss) but predicted item memory only in the older group. Hippocampal effects exclusively predicted source memory, and the magnitude of these effects did not reliably differ between the age groups. In the older group only, IFG and hippocampal encoding effects were positively correlated across participants with memory performance. Similar findings were evident in the extra-IFG regions demonstrating encoding effects. With the exception of the age-dependent relationship identified for hippocampal encoding effects, the present findings are broadly consistent with those from prior aging studies that employed verbal memoranda and tests of associative recognition. Thus, they extend these prior findings to include non-verbal materials and a different operationalization of episodic recollection. Additionally, the present findings suggest that the sensitivity in older adults of IFG encoding effects to subsequent memory performance reflects a more general tendency for cortical encoding effects to predict memory performance in this age group.

Key words: age-dependent; age-invariant; hippocampus; inferior frontal gyrus; recollection; subsequent memory effect

1. Introduction

Episodic memory – consciously accessible memory for personally experienced events -- declines disproportionately with increasing age in comparison with other forms of long-term memory (Craik 1986; Nilsson, 2003; Nyberg et al, 2012). This decline has attracted a range of explanations. One prominent account proposes an age-related impairment in processes supporting the encoding of episodic information into memory (e.g. Craik & Byrd, 1982; Werkle-Bergner et al, 2006; Old & Naveh-Benjamin, 2008; Craik & Rose, 2012; Friedman & Johnson, 2014). Motivated by this account, numerous studies have employed functional magnetic resonance imaging (fMRI) to investigate age differences in the neural correlates of encoding. Most of these studies adopted some version of the 'subsequent memory procedure' to identify neural activity differentiating successful and unsuccessful encoding (Wagner et al., 1998; Brewer et al, 1998; Paller & Wagner, 2002). In this procedure, neural activity elicited by study events is contrasted according to the judgments they attract on a subsequent memory test. The resulting 'subsequent memory effects' (SMEs) take two forms (for review, see Kim, 2011; Rugg et al., 2015): positive SMEs, when better remembered study items are associated with enhanced neural activity relative to less well remembered or forgotten items, and negative SMEs, when the effects exhibit the opposite pattern. Here, we focus exclusively on positive SMEs (henceforth, SMEs).

A wide variety of cortical regions have been reported to demonstrate SMEs, their loci dictated by such factors as the stimulus materials and the nature of the study task (see Rugg et al., 2015 for review). There is little evidence that SMEs are attenuated with age (e.g. Morcom et al., 2003; de Chastelaine et al., 2011; for reviews, see Maillet & Rajah, 2014 and Wang and Cabeza, 2016). Notably, age-invariant SMEs have consistently been reported in the hippocampus (e.g. Morcom et al., 2003; Duverne et al., 2009; Miller et al., 2008; de Chastelaine et al., 2011; 2016a; Bangen et al., 2012; Park et al., 2013), a region long established as playing a key role in episodic memory (Eichenbaum, 2017; Moscovitch et al., 2016). Of particular relevance here, in one study (de Chastelaine et al., 2016a) the magnitude of hippocampal SMEs demonstrated an age-invariant relationship (across samples of young, middle-aged and older adults) with subsequent associative recognition performance.

Whereas there is little evidence of an age-related attenuation of SMEs, SMEs have been reported to be enhanced, or more widely distributed across the cortex, in older than in younger adults (Wang & Cabeza, 2016). Notably, it has been reported that while SMEs in the left inferior frontal gyrus (IFG) and adjacent regions of the prefrontal cortex (PFC) do not differ reliably with age, SMEs in the right IFG are larger, or are only evident, in older adults (Morcom et al., 2003; Miller et al., 2008; Duverne et al., 2009; Spaniol & Grady, 2012; de Chastelaine et al., 2016a; but see de Chastelaine et al. 2011 for a null finding). These findings are examples of what has been termed age-related ‘right frontal over-recruitment’ (Cabeza et al., 1997; Logan et al., 2002; see Grady, 2012 for review). Their functional significance is unclear. According to one account, right frontal over-recruitment reflects the engagement of right prefrontal cortex in compensation for age-related decline in the functional capacity of cortical regions in the left hemisphere (e.g. Cabeza et al., 1997; Cabeza, 2002; Reuter-Lorenz & Park, 2014; for reviews see Grady, 2012; Cabeza et al. 2018). Alternatively, over-recruitment might be deleterious, reflecting, for example, reduced inter-hemispheric inhibition (Buckner & Logan, 2002; Logan et al., 2002; but see de Chastelaine et al., 2011) or, as suggested by Morcom et al. (2003), a weakening of cortical specialization (cf. Li et al., 2001; Koen & Rugg, 2019).

Several studies have addressed the functional significance of prefrontal SMEs in older adults by examining the relationship across participants between the size of the effects and subsequent memory performance. The assumption underlying this approach is that a positive relationship is indicative that the processes reflected by the SMEs are beneficial for encoding, whereas a negative relationship would suggest that the effects reflect processes detrimental to encoding (but see Cabeza et al., 2018 for qualification). To date, three studies have reported that the relationship between right prefrontal SMEs and memory performance is negative, that is, larger SMEs are predictive of lower subsequent memory performance (Duverne et al., 2009; Miller et al., 2008; de Chastelaine et al., 2011). In a follow-up study to de Chastelaine et al. (2011) that employed the same experimental memory task (associative recognition), de Chastelaine et al. (2016a) replicated the prior study by identifying a positive relationship between SMEs in the left IFG and memory performance in older, but not younger, participants. In striking contradiction to the prior findings, however, an age-dependent positive relationship was also identified in the *right* IFG.

de Chastelaine et al. (2016a) proposed that the age-dependent relationship between left IFG SMEs and subsequent memory performance reflects the region’s role as a ‘bottleneck’ that mediates the efficacy of episodic encoding in older adults. According to this proposal, early-life individual differences in left IFG function combine with age-related degradation of the region to determine its functional capacity in later life. By late adulthood this process has progressed sufficiently for variability in residual functional capacity (indexed by SMEs) to become a determinant of successful episodic encoding.

The finding by de Chastelaine et al. (2016a) of an age-dependent positive relationship between right IFG SMEs and subsequent memory performance can be accommodated by a similar account. The more prevalent finding of a negative relationship is, however, more challenging to explain, as are the factors that determine the direction of the relationship. de Chastelaine et al. (2016a) proposed that the direction depends on whether the encoded memory representations reflected in right IFG SMEs are accessible on the later memory test. They conjectured that the opposing correlations between right IFG SMEs and memory performance in their initial and subsequent studies arose because of a difference between the two studies in the amount of study test overlap: whereas participants' memories were tested outside of the scanner in de Chastelaine et al. (2011), the subsequent memory test was administered inside the scanner in the later study, reinstating the study context more fully and facilitating access to right IFG-dependent memory representations.

Here, we sought to build on and extend the findings of de Chastelaine et al. (2011, 2016a) and related studies. Rather than associative recognition of word pairs, we employed a source memory procedure as the experimental memory test and used pictures of objects as the experimental items. Like associative recognition judgments, accurate source judgments depend heavily on the retrieval of qualitative information about a past event (episodic recollection), and hence tests of source memory also allow the neural correlates of successful episodic encoding to be identified.

The primary aim of the present study was to assess whether the findings common to the studies of de Chastelaine et al. (2011, 2016a) can be reproduced when episodic memory is assessed with a very different type of memory test and experimental material. The findings in question are: age invariance in the magnitude of hippocampal and left IFG SMEs, age invariance in the relationship between hippocampal SMEs and memory performance, and an age dependent relationship between left IFG SMEs and later memory performance. If these findings generalize across memory tests as diverse as word-pair associative recognition and pictorial source memory this would provide strong support for the proposal that the aforementioned regions make task- and material-independent contributions to episodic memory encoding in young and older adults.

A second aim of the study was to examine SMEs in the right IFG. As was noted above, several studies have reported that SMEs in this region demonstrate 'age-related over-recruitment', although this is not an invariable finding. In addition, findings concerning the direction of the relationship between right IFG SMEs and later memory performance are mixed, and seem to depend on subtle aspects of the experimental context. The present study afforded the opportunity to further examine the role of age in moderating right IFG SMEs and their relationship with memory performance.

Of importance, the experimental memory test employed in the present study (see also Mattson et al., 2014) was designed to mitigate the confounding effects of memory strength on the experimental contrasts employed to operationalize successful encoding of items that go on to attract accurate vs. inaccurate source judgments (Squire et al. 2007; Wais et al. 2011). We achieved this by requiring participants to provide confidence ratings for their item and source judgments. Test items receiving a “confident old” item judgment were segregated according to whether they went on to receive an accurate, confident source judgment or an inaccurate/uncertain judgment. Thus, the contrast between study items that later received accurate vs. inaccurate source judgments permitted identification of neural correlates of the encoding of strong item–context associations that were unconfounded by differences in item memory strength. Correspondingly, the contrast between test items later receiving inaccurate source judgments and those misclassified as unstudied permitted the identification of the neural correlates of the encoding of strong item memories in the absence of information diagnostic of source (as we discuss later, this is not equivalent to item memories that are devoid of any contextual information).

2. Methods

The present study was first described in a report that focused exclusively on ‘pre-stimulus’ subsequent memory effects (Liu et al., 2021). The descriptions of the study participants, experimental procedures and behavioral results are presented here for the convenience of the reader, and not because they contain new information. The fMRI analyses described below, and the resulting findings, have not been published previously.

2.1 Participants

Data from 55 healthy adults, comprising 28 young adults (14 females) aged between 18 and 30 years (mean age: 23 years) and 27 older adults aged between 65 and 77 years (mean age: 69 years, 14 females) were analyzed and are reported below. All participants were right-handed, with normal or corrected-to-normal vision, and were free from neurological, psychiatric, and cardiovascular disease or any contraindication for MRI. Imaging data were collected from an additional 5 participants who were excluded from the fMRI analyses due to an insufficient number of trials in critical conditions (2 young and 1 older adult), an incidental MRI finding (1 older adult), or a programming error (1 older adult).

2.2 Neuropsychological testing

All participants undertook a battery of standardized neuropsychological tests prior to the day of the MRI session. The battery included the Mini-Mental State Examination (MMSE), the California Verbal Learning Test-II (CVLT; Delis et al., 2000), Wechsler Logical Memory Tests 1 and 2 (Wechsler, 2009), Trail Making tests A and B (Reitan & Wolfson, 1985), the Symbol Digit Modalities test (SDMT; Smith, 1982), the F-A-S subtest of the Neurosensory Center Comprehensive Evaluation for Aphasia (Spreen & Benton, 1977), the WAIS–R subtests of forward and backward digit span (Wechsler, 1981), a category fluency test (Benton, 1968), Raven's Progressive Matrices (List 1, Raven et al., 2000) and the Wechsler Test of Adult Reading (WTAR; Wechsler, 2001). To minimize the likelihood of including participants with mild cognitive impairment, individuals were excluded if they scored < 27 on the MMSE, > 1.5 SD below age norms on any standardized memory test, > 1.5 SD below age norms on two or more standardized non-memory tests, or if their full-scale IQ as estimated from the WTAR was < 100.

2.3 Materials

Psychophysics Toolbox 3.0 (http://psychtoolbox.org) implemented in Matlab 2017b (www.mathworks.com) was used to present the experimental stimuli and to record behavioral responses. Stimuli were centrally presented over a gray background and viewed via a mirror mounted above the scanner head-coil. The experimental items comprised a pool of 270 color images of everyday objects, food items, and animals. Twenty-eight study and test lists were created, with each study item selected from the pool randomly and without replacement. The lists were administered to 28 yoked pairs of young and older participants. Each study list consisted of 180 images and was split into 5 blocks (36 stimuli per block). In the test phase, all images from the study phase, along with an additional 90 'new' images, were presented. Study and test lists were pseudorandomized such that participants were presented with no more than three consecutive trials containing the same class of images (for additional details, see Liu et al., 2021).

2.4 Procedure

2.4.1 Study Phase

A schematic of the study phase is illustrated in the top panel of Figure 1. Each trial began with a centrally located green fixation cross, presented for 500 ms, followed by a pre-stimulus cue (either a red "X" or "O") presented for 750 ms. This was followed by a white fixation cross that remained on the screen for either 1500 ms, 3500 ms, or 5500 ms (rectangular distribution). The study item was then presented for 1500 ms and was followed by a second white fixation cross which again varied randomly in duration between 1500 ms, 3500 ms, or 5500 ms. Participants were instructed to make a ‘shoebox’ judgment (“does the item depicted by the image fit into a shoebox?”) following the “X” cue, and a ‘location’ judgment (“is the item depicted by the image more likely to be found indoors or outdoors?”) following the “O” cue. Participants used different hands (counterbalanced across participants) to make the two judgments. The index and middle fingers were associated with “Indoors/Fit inside a shoebox” and “Outdoors/Does not fit inside a shoebox”, respectively. Participants were encouraged to respond as rapidly and as accurately as possible. Before entering the scanner, participants were given detailed instructions about the study tasks and completed 3 practice study phases (for more details about the practice phase, see Liu et al., 2021). Participants were not informed of the nature of the post-scan memory test.

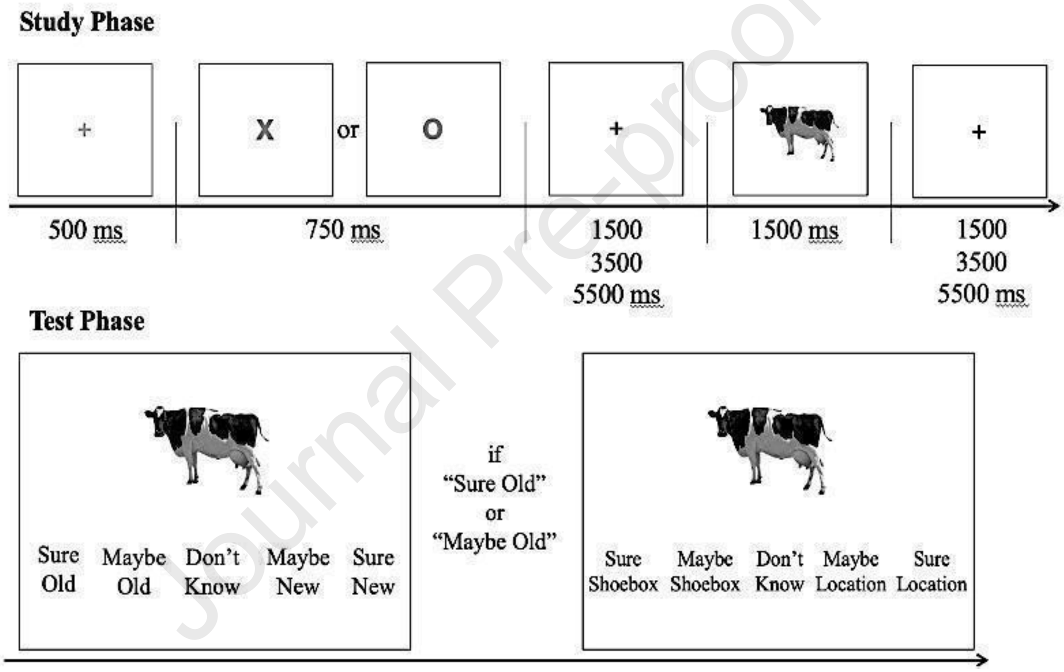

Figure 1. Schematic of the encoding task and subsequent memory test. At encoding, participants were instructed to indicate whether the item depicted by the image “fits into a shoebox” (X – shoebox trials); or “is more likely to be found indoors or outdoors” (O – location trials). At test, participants were instructed i) to make an item memory judgement (signaling confidence), and ii) for each item judged “old”, to then judge the study task associated with the item (again signaling confidence in the judgment).

2.4.2 Test Phase

Participants undertook the memory test outside the scanner on a laptop computer approximately 15 minutes after completion of the study phase. As is illustrated in the bottom panel of Figure 1, they were instructed to make memory judgments that incorporated confidence ratings. The test first required a five-way item memory judgment on each item (“Sure Old”, “Maybe Old”, “Don’t know”, “Maybe New”, “Sure New”) by pressing one of five designated keys on the keyboard. For any item endorsed “Old”, participants went on to make a source memory judgment about the task associated with the item at study, using the response alternatives, “Sure Location”, “Maybe Location”, “Don’t Know”, “Maybe Shoebox”, and “Sure Shoebox”. Participants were required to make both test judgments within a 10 sec window following item onset, after which the trial timed out and the next trial was initiated. They were encouraged to use the entire range of confidence ratings. Rests breaks were provided between each of the three test blocks. Before the test proper, participants completed a practice test block in which the items employed in the practice session preceding the study phase were intermixed with new items.

2.5 fMRI Data Acquisition

Functional and anatomical images were acquired from a 3T Philips Achieva MRI scanner (Philips Medical Systems) equipped with a 32-channel head coil. Functional images were acquired with a T2* weighted blood oxygen level dependent (BOLD) multiband echoplanar (EPI) sequence (flip angle = 70°, FOV = 200 * 240 mm, TR = 1.5 s, TE = 30 ms, multiband factor = 2). EPI volumes comprised 44 slices (inter-slice gap of 0.5 mm) with isotropic 2.5 mm voxels. Slices were acquired in an interleaved order and oriented parallel to the AC-PC line. Anatomical images were acquired with a T1-weighted magnetization-prepared rapid gradient echo (MPRAGE) pulse sequence (FOV = 256 × 256 mm, 1×1×1mm isotropic voxels, 176 slices, sagittal acquisition).

2.6 Behavioral data analysis

Trials that received multiple responses, no response, or a response with the incorrect hand during the study phase were excluded from behavioral and subsequent fMRI analyses. We computed item memory accuracy (Pr) and source accuracy (pSR) from the memory test performed outside of the scanner. Pr was computed as the difference between the hit rate for studied items (regardless of confidence or source memory accuracy) and the false alarm rate to new items, discounting items accorded a ‘don’t know’ judgment. pSR was derived from a guessing-corrected single high threshold model (Snodgrass & Corwin, 1988; Park & Rugg, 2009; Mattson et al, 2014) using the formula: [pSource Hit - 0.5 * (1 - pSource Don’t Know)] / [1 - 0.5 * (1 - pSource Don’t

Know)]. To allow examination of age differences in the memory strengths of items attracting confident item and source judgments we computed accuracy metrics (Wixted et al., 2010) for these judgments according to the formulae pConfident Hit/(pConfident Hit + pConfident False Alarm) and pConfident Source Correct/(pConfident Source Correct + pConfident Source Incorrect). Age differences in Pr, pSR and the item and source accuracy metrics were examined using independent samples t-tests.

2.7 fMRI Data Analysis

2.7.1 fMRI data preprocessing

The functional data were preprocessed with Statistical Parametric Mapping (SPM12, Wellcome Department of Cognitive Neurology, London, UK) implemented in Matlab 2017b (www.mathworks.com). The data were reoriented, subjected to a two-pass realignment procedure with images realigned to the first image of a session and then to the mean EPI image, and corrected for slice acquisition time differences using sinc interpolation referenced to the time of acquisition of the 12th slice. Images were then spatially normalized to a study-specific EPI template following previous published procedures (de Chastelaine et al., 2011; 2016a) and smoothed with an 8 mm full width at half-maximum Gaussian kernel. The data from the five study sessions were concatenated using the spm_concatenate.m function prior to the implementation of the first stage general linear model (GLM).

2.7.2 fMRI analyses

The functional data were analyzed in two stages. In the first stage each participant’s data were modeled to estimate the neural activity elicited by the different classes of study event. The activity was modeled by convolving a delta function time-locked to the onset of each study item with SPM’s canonical hemodynamic response function. The design matrix contained three events of interest (cf. Mattson et al., 2014): i) ‘source hits’ – studied items that later attracted correct and confident item and source memory judgments; ii) ‘source misses’ – studied items that later attracted correct and confident item memory judgments, but incorrect, low confidence or “don’t know” source judgments, and iii) ‘item misses’ – studied items that later attracted a new, a low confidence old, or a “Don’t Know” item memory response. The inclusion of low confidence correct responses in the item and source miss bins was necessary to give enough trials for the fMRI analyses. Source hit and source miss trials were restricted to studied items that received high confidence item judgments to mitigate the confounding of item memory strength with source memory accuracy (see Introduction). The design matrix also included regressors to model events of no interest, including a single regressor for studied items later attracting correct but low confidence source judgments and trials where no response or multiple responses were given, six motion regressors, spike covariates for volumes showing transient displacement > 1 mm or > 1° in any direction, and constants modelling the mean signal in each scan session.

Participant-specific parameter estimates were carried forward to a second GLM and subjected to a 2 (age group) by 3 (memory judgment) mixed-design whole brain ANOVA (note that as implemented in SPM, ANOVA models employ a single, pooled error term). The ANOVA was height-thresholded at $p < 0.001$, and clusters were deemed significant if they exceeded a $p < 0.05$ FWE corrected cluster extent threshold (corresponding to $k > 60$). Clusters exhibiting a main effect of memory condition that contained a positive SME (no clusters were identified that demonstrated a significant age x memory condition interaction at the whole brain level) were designated as regions of interest (ROIs) and subjected to further analysis.

In the case of the left IFG, which demonstrated an SME that extended along much of its extent (see Figure 2), mean parameter estimates were extracted from all voxels within 5-mm radius spheres centered on the peak voxels localized within each of the three sub-divisions of the region (corresponding to BA44, BA45 and BA47, see supplemental Table 1; cf. de Chastelaine et al., 2011). An initial ANOVA of these data employing the factors of age group, sub-region and memory judgment (source hit, source miss, item miss) failed to identify any reliable interactions between sub-region and the remaining factors (see supplemental results). Accordingly, the parameter estimates were averaged to provide a single estimate of LIFG activity for each memory judgment. For each of the other cortical ROIs (including the right IFG) mean parameter estimates were extracted from 5mm radius spheres centered on the peak voxel and up to two sub-peaks that were separated from the peak and each other by a Euclidian distance of at least 9mm (see supplemental Table 1 for the number and the co-ordinates of the sub-peaks in each ROI). The mean parameter estimates were averaged across the peaks to provide a single estimate of regional activity. In the case of left and right hippocampus, we employed a sample-specific bilateral hippocampal mask to identify the peak voxels of clusters that fell within the hippocampus. Mean parameter estimates of the left and right hippocampus were computed from the voxels falling within a 3mm radius sphere of each peak.

The resulting participant-specific average parameter estimates were subjected to three ANOVAs. The first ANOVA was directed at the IFG, and employed the factors of age group, hemisphere, and memory judgment. The second ANOVA, which employed an identical design, was directed at the estimates derived from the hippocampus. A final ANOVA was employed to analyze the data from the 8 extra-IFG cortical ROIs, and included the factors of age group, ROI and memory judgment. Effects were deemed significant at $p < 0.05$ after Geisser-Greenhouse correction for non-sphericity. The significance levels of any follow-up tests were subjected to family-wise correction for multiple comparisons with the Bonferroni procedure. It is important to note that, given the criterion for ROI definition, a main effect of memory judgment in these ANOVAs is a foregone conclusion, and therefore is not reported. The ordering of the effects between different memory judgments, and interactions between memory judgment, age group and ROI, are free to vary, however.

In the light of prior findings (see Introduction) we employed multiple regression to test for relationships between item and source memory performance and encoding-related neural activity in the hippocampus and IFG. For each region, separate models were constructed using age group, SME magnitude, and their interaction term as predictors of item and source memory performance respectively. In a third, exploratory, set of analyses we employed multiple regression to examine relationships between extra-IFG cortical SMEs and memory performance. Preliminary analyses revealed that item (source miss – item miss) and source (source hit – source miss) SMEs in all regions (IFG, hippocampus, and extra-IFG cortical regions) demonstrated robust negative correlations (ranging between $r = -.485$, $p < 0.001$, and $r = -.298$, $p < 0.05$). Because of this negative dependency between the two classes of SME, and the attendant interpretational difficulties, we elected to employ a single aggregate SME metric in the form of the difference between the parameter estimates associated with source hits and item misses. This approach has the additional advantage of halving the number of regression models estimated for each region of interest, reducing the likelihood of Type I error.

3. Results

3.1 Neuropsychological Test Performance

Neuropsychological test performance is fully described in Liu et al. (2021). Briefly, relative to their younger counterparts, older adults demonstrated poorer performance on tests of declarative memory, reasoning, processing speed, and category fluency. Overall, the patterning of the test scores across the age groups was consistent with previous reports from studies employing similar participant samples (e.g. de Chastelaine et al., 2011, 2016a).

3.2 Behavioral performance

Behavioral performance on the study phase was also reported previously (Liu et al., 2021). Here we re-report performance from the test phase because of its relevance to the current imaging findings. The analyses of memory strength reported below have not been described previously.

3.2.1 Item Memory

Item memory performance is summarized in Table 1. There was no significant difference in item recognition accuracy (Pr) across the age groups (young: M = 0.70, SD = 0.13; older: M = 0.69, SD = 0.13; t_{53} = 0.13, p = 0.89, Cohen's d = 0.04).

Table 1. Mean and SD for the proportions of item memory judgments for old and new trials by age group and confidence rating.

	Young Adults		Older Adults	
	Old items	New items	Old items	New items
Confident Old	0.68 (0.16)	0.02 (0.05)	0.75 (0.13)	0.07 (0.06)
Unconfident Old	0.11 (0.10)	0.07 (0.09)	0.04 (0.06)	0.06 (0.07)
Don't Know	0.05 (0.06)	0.07 (0.10)	0.04 (0.04)	0.06 (0.06)
Unconfident New	0.07 (0.05)	0.27 (0.22)	0.04 (0.04)	0.12 (0.15)
Confident New	0.10 (0.10)	0.58 (0.31)	0.14 (0.09)	0.73 (0.22)

3.2.2 Source Memory

Source memory performance is summarized in Table 2. Given the strong prior evidence for an age-related decline in source memory (for review, Spencer & Raz, 1995; Old & Naveh-Benjamin, 2008; Koen & Yonelinas, 2014), age differences in source memory were evaluated with a one-tailed (directional) t-test. Source accuracy (pSR) was significantly higher in the young group (young: M = 0.58, SD = 0.17; older: M = 0.51, SD = 0.14; t_{53} = 1.77, p = 0.04, Cohen's d = 0.48).

3.2.3 Memory accuracy (strength)

Accuracy of highly confident item judgments was 0.98 (SD = 0.04) and 0.96 (0.05) for the young and older groups respectively. The analogous metrics for confident source judgments were 0.91 (SD = 0.08) and 0.82 (0.07). These measures were entered in to a 2 (age group) x 2 (memory judgment: item vs. source) ANOVA. The ANOVA gave rise to main effects of age group ($F_{1, 53}$ = 15.65, p < 0.001, partial η^2 = 0.23) and judgment ($F_{1, 53}$ = 121.53, p < 0.001, partial η^2 = 0.70) and to a significant interaction between the two factors ($F_{1, 53}$ = 12.83, p = 0.001, partial η^2 = 0.19). Post hoc pairwise tests revealed that in both age groups item accuracy exceeded that for source accuracy (young: t_{27} = 5.42, p < 0.001, Cohen's d = 1.02; older: t_{26} = 10.03, p < 0.001, Cohen's d = 1.93). However, whereas there was a sizeable age difference in source accuracy (t_{53} = 4.25, p < 0.001, Cohen’s d = 1.15), the effect of age on item memory did not attain significance, even before correction for multiple comparisons ($t_{53} = 1.99$, $p = 0.051$, Cohen’s d = 0.54).

Table 2. Means and SDs for the proportion of source memory judgments for correctly recognized study items.

	Young Adults		Older Adults	
	Confident Old	Unconfident Old	Confident Old	Unconfident Old
Confident Source Correct	0.61 (0.19)	0.11 (0.23)	0.60 (0.17)	0.06 (0.20)
Unconfident Source correct	0.19 (0.15)	0.41 (0.26)	0.15 (0.15)	0.32 (0.37)
Source Don’t Know	0.06 (0.07)	0.20 (0.25)	0.04 (0.05)	0.04 (0.11)
Unconfident Source Incorrect	0.07 (0.06)	0.23 (0.22)	0.07 (0.06)	0.23 (0.33)
Confident Source Incorrect	0.06 (0.06)	0.02 (0.04)	0.13 (0.07)	0.06 (0.20)

3.3 fMRI results

The mean (SD, range) trial numbers for source hits, source misses, and item misses in the young group were 75 (35; 10-135), 22 (12; 8 – 58), 55 (28; 15-115), respectively, and 80 (29; 21-135), 32 (12; 13-115) and 44 (23; 8-64) in the older group. As detailed in Table 3 and illustrated in Figure 2, age-invariant positive SMEs were identified in 10 cortical regions, including the left and right IFG, and in bilateral anterior hippocampus. As detailed in the supplemental materials, the findings reported below for the LIFG and hippocampus were fully replicated when we employed regions of interest (ROIs) that were defined *a priori* rather than by the present whole brain analysis.

Table 3. Regions identified from the whole brain analysis that demonstrated positive subsequent memory effects. The MNI coordinate of the peak of each cluster is listed.

Region	MNI			k	z
	x	y	z		
L inferior frontal gyrus (IFG)	-48	31	-10	1033	7.21
L dorsomedial prefrontal cortex (DMPFC)	-8	48	50	586	5.40
L anterior hippocampus	-18	-7	-18	69	4.68

L fusiform gyrus	-33	-40	-25	1163	6.74
L posterior cingulate cortex	-6	-57	8	64	4.39
L superior occipital gyrus	-36	-92	20	209	4.85
R IFG	55	38	13	210	5.51
R orbitofrontal gyrus	37	38	-15	114	6.13
R parahippocampal cortex/entorhinal cortex	22	-15	-25	122	5.11
R anterior hippocampus	22	-10	-15	32	4.28
R fusiform gyrus	27	-35	-25	689	6.26
R superior occipital gyrus	40	-87	23	108	4.47

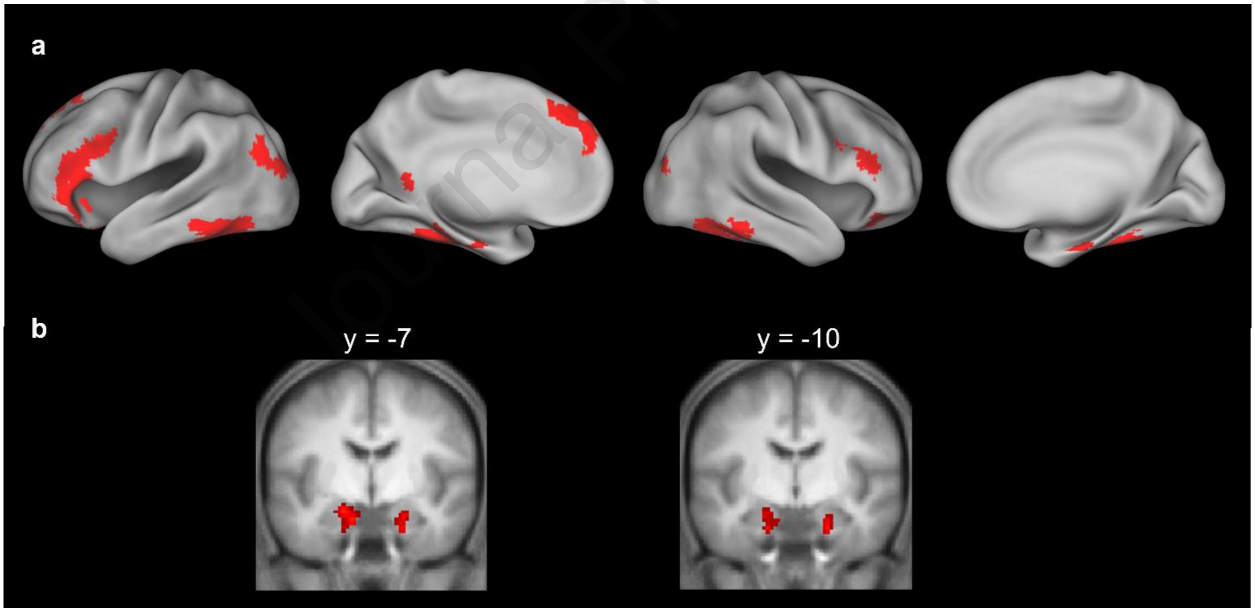

Figure 2. Brain regions identified by the whole brain analyses that demonstrated significant positive subsequent memory effects. a: significant clusters, overlaid onto a standardized PALS-B12 surface in Caret (Van Essen & Dierker, 2007). b: left and right anterior hippocampal SMEs overlaid on the across-participants mean T1-weighted structural image.

3.3.1 IFG SMEs

Parameter estimates from the left and right IFG are illustrated in Figure 3. As is evident from Table 4, the initial 2 (age group) x 3 (memory judgment) x 2 (hemisphere) ANOVA revealed a main effect of memory judgment and memory judgment x age group interaction. No effects involving the factor of hemisphere attained significance. The memory judgment x age group interaction was elucidated by two follow-up ANOVAs, the first employing the factors of age group, hemisphere and a memory judgment factor comprising source correct and source miss judgments, and the second age group, hemisphere and a judgment factor comprising source miss and item miss judgments. The first of these analyses revealed a main effect of memory judgment which was qualified by a memory judgment x age group interaction. As is evident from Figure 3, the interaction appears to be driven by the presence of source SMEs in the young, but not the older group's data. Within-group pairwise contrasts confirmed this impression (for young, $t_{27} = 5.05$, $p < 0.001$, Cohen's d = 0.95; for older, $t_{26} = 1.36$, $p = 0.184$, Cohen's d = 0.26). By contrast, the second ANOVA gave rise solely to a main effect of memory judgment, indicative of a robust, age-invariant item SME.

Table 4. Results of mixed-design ANOVAs of parameter estimates derived from the left and right IFG (bold values denote significance at the p < 0.05 level). A: results from the full ANOVA model contrasting source correct, source miss and item miss judgments. B: Results from the model contrasting source correct and source miss judgments. C: Results from the model contrasting source miss and item miss judgments.

A	
Memory judgment	**$F_{2, 106} = 36.85$, $p < 0.001$, partial $\eta^2 = 0.41$**
Age group	$F_{1, 53} = 2.00$, $p = 0.163$, partial $\eta^2 = 0.04$
Hemisphere	$F_{1, 53} = 0.07$, $p = 0.788$, partial $\eta^2 = 0.00$
Memory judgment x age group	**$F_{2, 106} = 5.42$, $p = 0.006$, partial $\eta^2 = 0.09$**
Hemisphere x age group	$F_{1, 53} = 1.03$, $p = 0.314$, partial $\eta^2 = 0.02$
Memory judgment x hemisphere	$F_{2, 106} = 2.27$, $p = 0.108$, partial $\eta^2 = 0.04$
Memory judgment x hemisphere x group	$F_{2, 106} = 0.14$, $p = 0.873$, partial $\eta^2 = 0.00$
B	
Memory judgment	**$F_{1, 53} = 22.37$, $p < 0.001$, partial $\eta^2 = 0.30$**

Age group	$F_{1, 53} = 2.29$, $p = 0.136$, partial $\eta^2 = 0.04$
Hemisphere	$F_{1, 53} = 0.43$, $p = 0.513$, partial $\eta^2 = 0.00$
Memory judgment x age group	**$F_{1, 53} = 8.88$, $p = 0.004$, partial $\eta^2 = 0.14$**
Hemisphere x age group	$F_{1, 53} = 1.05$, $p = 0.310$, partial $\eta^2 = 0.02$
Memory judgment x hemisphere	$F_{1, 53} = 0.00$, $p = 0.957$, partial $\eta^2 = 0.00$
Memory judgment x hemisphere x group	$F_{1, 53} = 0.16$, $p = 0.693$, partial $\eta^2 = 0.00$
C	
Memory judgment	**$F_{1, 53} = 16.67$, $p < 0.001$, partial $\eta^2 = 0.24$**
Age group	$F_{1, 53} = 0.78$, $p = 0.382$, partial $\eta^2 = 0.01$
Hemisphere	$F_{1, 53} = 0.00$, $p = 0.951$, partial $\eta^2 = 0.00$
Memory judgment x age group	$F_{1, 53} = 0.04$, $p = 0.847$, partial $\eta^2 = 0.00$
Hemisphere x age group	$F_{1, 53} = 0.75$, $p = 0.390$, partial $\eta^2 = 0.01$
Memory judgment x hemisphere	$F_{1, 53} = 3.65$, $p = 0.061$, partial $\eta^2 = 0.06$
Memory judgment x hemisphere x group	$F_{1, 53} = 0.01$, $p = 0.915$, partial $\eta^2 = 0.00$

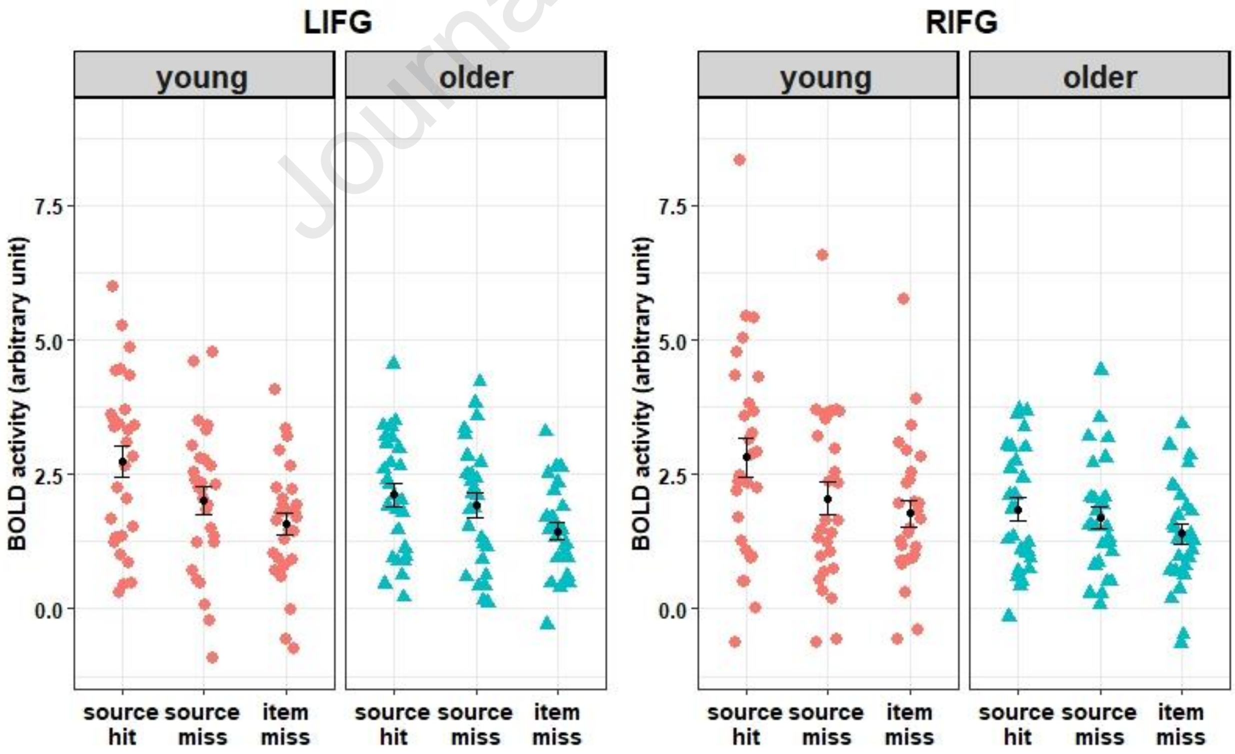

Figure 3. Parameter estimates of fMRI BOLD activity elicited by study items in left and right IFG that demonstrated positive subsequent memory effects. Black dots represent the group means and the error bars signify standard errors. Across hemispheres, significant source SMEs (source hit > source miss) were evident in young but not older adults. Age-invariant item SMEs (source miss > item miss) were identified in both left and right IFG.

3.3.2 Hippocampus SMEs

The hippocampal parameter estimates are illustrated in Figure 4. As is evident from Table 5, the initial ANOVA gave rise to a hemisphere x age group interaction and a memory judgment x age group interaction, but no other effects beyond that of memory judgment. As for the IFG, the interaction was followed up with two subsidiary ANOVAs. The ANOVA contrasting source hits and source misses gave rise to a reliable main effect of memory judgment and a hemisphere x age group interaction. The memory judgment x age group interaction was close to but did not attain significance. Of importance, when the ANOVA was repeated as an ANCOVA, controlling for the effect of source memory strength, the interaction was far from significant ($F_{1, 53} < 1$; very similar findings were evident when pSR was employed as the covariate). Thus, the magnitude of the older adults' source SMEs was the equivalent of that expected of young adults performing at the same level (cf. de Chastelaine at al., 2016b; Rugg, 2017). The ANOVA testing for item SMEs gave rise to a main effect of age and a hemisphere x memory judgment interaction. Separate ANOVAs conducted on the data from each hemisphere failed to identify significant SMEs in either case (ps > 0.129).

Table 5. Results of mixed-design ANOVAs in left and right hippocampus (bold values denote significance at the p < 0.05 level). A: results from the full ANOVA model contrasting source correct, source miss and item miss judgments. B: Results from the model contrasting source correct and source miss judgments. C: Results from the model contrasting source miss and item miss judgments.

A	
Memory judgment	**$F_{2, 106} = 17.86$, $p < 0.001$, partial $\eta^2 = 0.25$**
Age group	$F_{1, 53} = 3.11$, $p = 0.083$, partial $\eta^2 = 0.06$
Hemisphere	$F_{1, 53} = 0.86$, $p = 0.357$, partial $\eta^2 = 0.02$

Memory judgment x age group	**$F_{2, 106} = 3.65, p = 0.029$, partial $\eta^2 = 0.06$**
Hemisphere x age group	**$F_{1, 53} = 4.90, p = 0.031$, partial $\eta^2 = 0.08$**
Memory judgment x hemisphere	$F_{2, 106} = 2.62, p = 0.078$, partial $\eta^2 = 0.05$
Memory judgment x hemisphere x group	$F_{2, 106} = 0.11, p = 0.894$, partial $\eta^2 = 0.00$
B	
Memory judgment	**$F_{1, 53} = 22.33, p < 0.001$, partial $\eta^2 = 0.30$**
Age group	$F_{1, 53} = 1.38, p = 0.245$, partial $\eta^2 = 0.03$
Hemisphere	$F_{1, 53} = 0.02, p = 0.900$, partial $\eta^2 = 0.00$
Memory judgment x age group	$F_{1, 53} = 3.66, p = 0.061$, partial $\eta^2 = 0.06$
Hemisphere x age group	**$F_{1, 53} = 4.47, p = 0.039$, partial $\eta^2 = 0.08$**
Memory judgment x hemisphere	$F_{1, 53} = 1.13, p = 0.292$, partial $\eta^2 = 0.02$
Memory judgment x hemisphere x group	$F_{1, 53} = 0.19, p = 0.663$, partial $\eta^2 = 0.00$
C	
Memory judgment	$F_{1, 53} = 0.26, p = 0.610$, partial $\eta^2 = 0.00$
Age group	**$F_{1, 53} = 6.06, p = 0.017$, partial $\eta^2 = 0.10$**
Hemisphere	$F_{1, 53} = 0.81, p = 0.373$, partial $\eta^2 = 0.01$
Memory judgment x age group	$F_{1, 53} = 0.37, p = 0.545$, partial $\eta^2 = 0.00$
Hemisphere x age group	$F_{1, 53} = 3.58, p = 0.064$, partial $\eta^2 = 0.06$
Memory judgment x hemisphere	**$F_{1, 53} = 4.90, p = 0.031$, partial $\eta^2 = 0.08$**
Memory judgment x hemisphere x group	$F_{1, 53} = 0.00, p = 0.949$, partial $\eta^2 = 0.00$

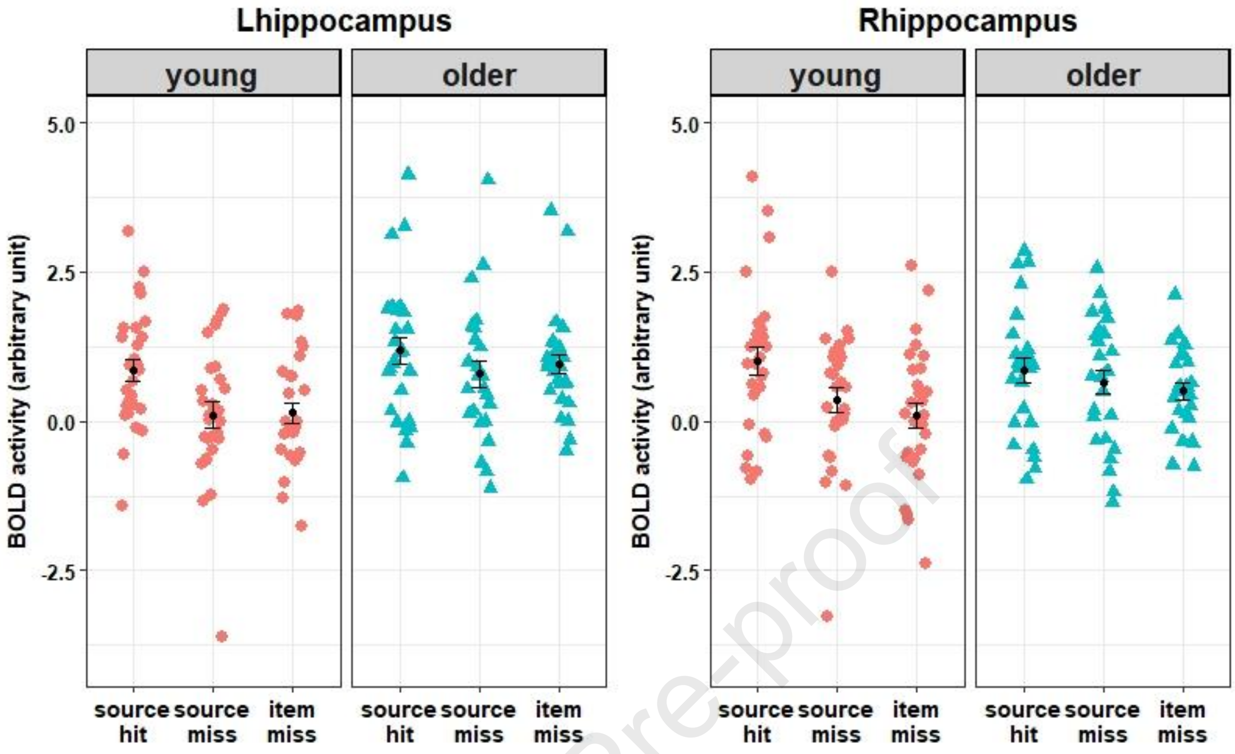

Figure 4. Parameter estimates of fMRI BOLD activity elicited by study items in left and right hippocampus that demonstrated positive subsequent memory effects. Black dots represent the group means and the error bars signify standard errors. Significant, age-invariant source SMEs were evidence in both left and right hippocampus.

3.3.3 Extra-IFG cortical SMEs

The parameter estimates for the extra-IFG SMEs (collapsed across ROIs) are illustrated in Figure 5. Results of the ANOVAs conducted in these regions are given in Table 6. As is evident from the table, the initial ANOVA gave rise to a main effect of ROI and to an interaction between memory judgment and age group. The subsidiary ANOVA testing for source SMEs gave rise to a main effect of ROI, a main effect of memory judgment and to a reliable memory judgment by age-group interaction. As for the IFG, the interaction appears to be driven by the presence of a source SME in the young group only (see Figure 5). Pairwise contrasts on the estimates collapsed across the ROIs confirmed this impression (young: $t_{27} = 4.62$, $p < 0.001$, Cohen's d = 0.87; older: $t_{26} = 1.22$, $p = 0.234$, Cohen's d = 0.23). The ANOVA examining item SMEs gave rise to a main effect of ROI and a main effect of memory judgment but to a null effect for the judgment x age group interaction, indicative of an age-invariant item SME.

Table 6. Results of mixed-design ANOVAs in extra-IFG cortical regions (bold values denote significance at the p < 0.05 level). A: results from the full ANOVA model contrasting source correct, source miss and item miss judgments. B: Results from the model contrasting source correct and source miss judgments. C: Results from the model contrasting source miss and item miss judgments.

A	
Memory judgment	**$F_{2, 106} = 34.76, p < 0.001$, partial $\eta^2 = 0.40$**
Age group	$F_{1, 53} = 1.48, p = 0.229$, partial $\eta^2 = 0.03$
ROI	**$F_{3.54, 187.88} = 57.46, p < 0.001$, partial $\eta^2 = 0.52$**
Memory judgment x age group	**$F_{2, 106} = 5.70, p = 0.004$, partial $\eta^2 = 0.10$**
ROI x age group	$F_{3.54, 187.88} = 2.26, p = 0.073$, partial $\eta^2= 0.04$
Memory judgment x ROI	$F_{7.01, 371.35} = 1.91, p = 0.067$, partial $\eta^2 = 0.03$
Memory judgment x ROI x group	$F_{7.01, 371.35} = 0.97, p = 0.456$, partial $\eta^2 = 0.02$
B	
Memory judgment	**$F_{1, 53} = 17.17, p < 0.001$, partial $\eta^2 = 0.24$**
Age group	$F_{1, 53} = 2.35, p = 0.131$, partial $\eta^2 = 0.04$
ROI	**$F_{3.66, 193.96} = 53.16, p < 0.001$, partial $\eta^2 = 0.50$**
Memory judgment x age group	**$F_{1, 53} = 5.94, p = 0.018$, partial $\eta^2 = 0.10$**
ROI x age group	$F_{3.66, 193.96} = 2.27, p = 0.069$, partial $\eta^2 = 0.04$
Memory judgment x ROI	$F_{3.24, 171.77} = 1.17, p = 0.323$, partial $\eta^2 = 0.02$
Memory judgment x ROI x group	$F_{3.24, 171.77} = 0.32, p = 0.825$, partial $\eta^2 = 0.00$
C	
Memory judgment	**$F_{1, 53} = 16.76, p < 0.001$, partial $\eta^2 = 0.24$**
Age group	$F_{1, 53} = 0.23, p = 0.631$, partial $\eta^2 = 0.00$
ROI	**$F_{3.54, 187.59} = 58.51, p < 0.001$, partial $\eta^2 = 0.52$**
Memory judgment x age group	$F_{1, 53} = 0.36, p = 0.551$, partial $\eta^2 = 0.00$

ROI x age group	$F_{3.54,\ 187.59} = 2.17$, $p = 0.082$, partial $\eta^2 = 0.04$
Memory judgment x ROI	$F_{4.19,\ 221.89} = 0.95$, $p = 0.437$, partial $\eta^2 = 0.02$
Memory judgment x ROI x group	$F_{4.19,\ 221.89} = 1.53$, $p = 0.193$, partial $\eta^2 = 0.03$

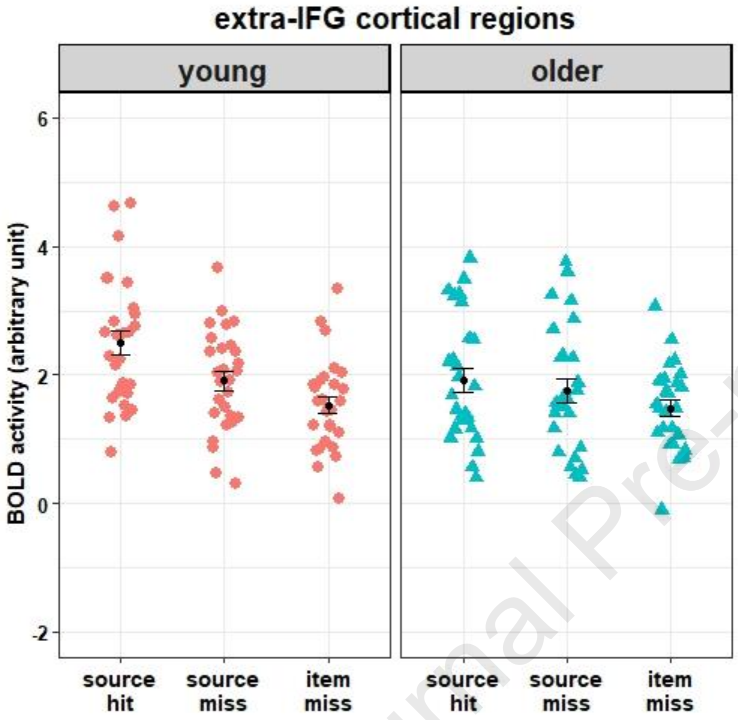

Figure 5. Parameter estimates of fMRI BOLD activity elicited by study items averaged across the extra-IFG cortical regions that demonstrated positive subsequent memory effects. Black dots represent the group means and the error bars signify standard errors. Across the extra-IFG cortical regions, significant source SMEs were evident in young adults only.

3.3.4 Main effects of age

At the request of a reviewer, we also identified regions demonstrating significant main effects of age. Compared to older adults, young adults demonstrated greater BOLD activity in bilateral occipital regions and in the left middle frontal gyrus. By contrast, older adults demonstrated greater activity than young adults in left premotor and precentral regions and in the right medial prefrontal cortex (see supplemental materials for more details).

3.3.5 Relationships between SMEs and memory performance

As detailed in the Methods section, we employed multiple regression to identify relationships between SMEs and item and source memory performance. Given our *a priori* interest in SMEs in the left and right IFG, these were modeled separately. In the case of the hippocampus, we averaged the SMEs across the hemispheres to give a single measure. Analogously, the regression model examining the relationship between extra-IFG cortical SMEs and memory performance employed as a predictor a single SME derived by averaging the SMEs across the 8 regions where the effects were detected.

The outcomes of the regression analyses are summarized in Table 4. Bivariate correlations between the two memory measures and the different SMEs are reported in Table 5 separately for each age group.

As is evident from Table 7, in no case did an SME reliably predict either item or source memory performance in an age-invariant manner. Significant interaction terms, indicative of age-dependent relationships, were identified in the models predicting Pr from left and right IFG SMEs, and in the models predicting pSR from hippocampal and extra-IFG cortical SMEs. As can be seen in Table 8, these interactions were driven by the tendency for correlations between SMEs and memory performance to be small and far from significant in the young group but sizeable and, prior to correction for multiple comparisons, largely reliable in the older age group. As indicated in the table, three of the correlations in the older age group survived correction for multiple comparisons across the family of 8 tests (corrected significance level $p < .00625$). These correlations were between the LIFG and Pr, and the hippocampus and extra-IFG cortical regions and pSR. Scatter plots depicting these relationships are illustrated in Figure 6. Each of the correlations remained significant after controlling for chronological age (partial rs > 0.489, ps < 0.012).

Table 7. Linear regression results for SMEs predicting item and source memory performance.

Predictor	B (SE)	beta	t	p
Left IFG SME predicting item memory				
Left IFG SME	0.002 (0.02)	0.02	0.10	0.922
Age group	-0.07 (0.05)	-0.28	-1.48	0.146

Left IFG SME x age group	**0.10 (0.04)**	**0.47**	**2.45**	**0.018**
Right IFG SME predicting item memory				
Right IFG SME	-0.02 (0.02)	-0.13	-0.80	0.430
Age group	-0.06 (0.05)	-0.23	-1.29	0.204
Right IFG SME x age group	**0.09 (0.05)**	**0.37**	**2.10**	**0.041**
Mean hippocampal SME predicting item memory				
Mean hippo SME	-0.03 (0.03)	-0.19	-0.95	0.345
Age group	-0.04 (0.05)	-0.16	-0.91	0.369
Mean hippo SME x age group	0.07 (0.05)	0.29	1.43	0.158
extra-IFG cortical SME predicting item memory				
extra-IFG cortical SME	0.005 (0.04)	0.02	0.12	0.908
Age group	-0.04 (0.06)	-0.16	-0.70	0.485
extra-IFG cortical SME x age group	0.08 (0.06)	0.31	1.40	0.169
Left IFG SME predicting source memory				
Left IFG SME	-0.002 (0.03)	-0.01	-0.08	0.938
Age group	**-0.13 (0.06)**	**-0.43**	**-2.16**	**0.035**
Left IFG SME x age group	0.09 (0.05)	0.33	1.65	0.105
Right IFG SME predicting source memory				
Right IFG SME	-0.01 (0.03)	-0.03	-0.20	0.843
Age group	**-0.12 (0.05)**	**-0.38**	**-2.18**	**0.034**
Right IFG SME x age group	0.09 (0.05)	0.30	1.74	0.087
Mean hippocampal SME predicting source memory				
Mean hippo SME	-0.04 (0.04)	-0.18	-0.93	0.354
Age group	**-0.13 (0.05)**	**-0.41**	**-2.50**	**0.016**
Mean hippo SME x age group	**0.13 (0.05)**	**0.44**	**2.38**	**0.021**
extra-IFG cortical SME predicting source memory				
extra-IFG cortical SME	-0.05 (0.05)	-0.20	-1.01	0.316
Age group	**-0.18 (0.06)**	**-0.57**	**-2.77**	**0.008**

extra-IFG cortical SME x age group	**0.18 (0.07)**	**0.54**	**2.63**	**0.011**

Table 8. Bivariate correlations between the two memory measures and the different SMEs in each age group (p values in parentheses).

	pr	pSR
Young		
Left IFG SME	0.02 (0.928)	-0.01 (0.946)
Right IFG SME	-0.15 (0.445)	-0.03 (0.863)
Mean hippocampal SME	-0.18 (0.348)	-0.16 (0.425)
extra-IFG cortical SME	0.02 (0.912)	-0.17 (0.394)
Older		
Left IFG SME	**0.57 (0.002)**	**0.43 (0.024)**
Right IFG SME	0.38 (0.053)	**0.42 (0.029)**
Mean hippocampal SME	0.21 (0.296)	**0.51 (0.006)**
extra-IFG cortical SME	**0.41 (0.036)**	**0.57 (0.002)**

Note. Significant correlations that did not survive correction for multiple comparisons are shown in grey.

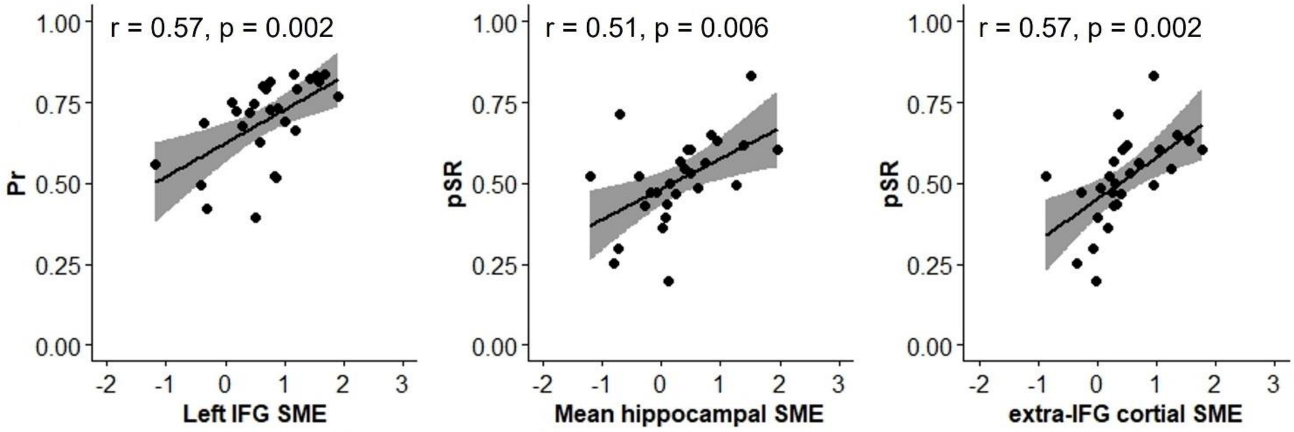

Figure 6. Left panel: scatter plot of the relationships between LIFG SMEs and item recognition accuracy (Pr). Center panel: relationship between hippocampal SMEs and source accuracy (pSR).

Right panel: relationship between extra-IFG cortical SMEs and source accuracy. All plots depict data from the older age group only. Shading around fitted lines represents 95% confidence intervals.

4. Discussion

The present study investigated the effects of age on encoding-related neural activity predictive of subsequent source and item memory performance. Motivated by prior findings (de Chastelaine et al., 2011, 2016a) we focused on positive SMEs in bilateral IFG and hippocampus. Robust SMEs were identified in the IFG in each age group: these included both source and item effects in the young group but an item effect only in the older group. SMEs in the right IFG demonstrated no evidence of age-related over-recruitment. Positive SMEs in a further 8 cortical regions demonstrated the same pattern as in the IFG: a combination of source and item effects in the young group, and item effects only in the older adults. Age-invariant source SMEs were identified in the hippocampus, while hippocampal item SMEs were undetectable. Positive relationships between memory performance and SMEs were identified in the older age group only; these relationships were especially strong in the left IFG, hippocampus, and extra-IFG cortical regions. Below, we expand on these findings.

4.1 Behavioral Performance

The behavioral findings from this study have been discussed previously (Liu et al., 2021) and are discussed here in an abbreviated fashion. Of importance, the strength of the memories supporting confident source judgments was markedly lower in the older than the young age group. By contrast, item memory strength did not differ reliably with age. As we discuss below, the age difference in source memory strength may have contributed to the failure to detect cortical source SMEs in the older age group. The present findings converge with prior reports (Hou et al., 2021b; Mark & Rugg, 1998) to indicate that restricting analyses to highly confident memory judgments does not eliminate age differences in memory strength.

We further note that, as in any study where source memory judgments are employed to operationalize recollection, it is not possible to rule out the possibility that at least some of the items attracting an unsuccessful source judgment elicited recollection of information that was uninformative of the source (‘non-criterial recollection’; Parks, 2007; Yonelinas & Jacoby, 1996). This possibility is especially likely in the present case because source misses comprised items that attracted high confidence item hits, which are frequently associated with subjective reports of recollection (Koen &

Yonelinas, 2010; Yonelinas, 2001). Furthermore, the source miss category included items attracting correct, low confidence source judgments. Although the accuracy of these judgments was markedly lower than that of the judgments made with high confidence, it was not at chance (see Table 2). Thus, it is possible that the finding that cortical SMEs invariably predicted successful item memory arose because episodic encoding was not entirely unsuccessful for the study items that went on to be categorized as source misses. By this account, the magnitudes of the source and item SMEs reflect the amount of episodic information encoded about the study event rather than neural correlates of encoding supporting successful versus unsuccessful recollection.

4.2 fMRI results

Both young and older adults demonstrated robust item SMEs in all cortical regions where positive SMEs were identified. However, whereas these regions also evidenced source SMEs in the young adults, source effects could not be identified in the older group. As already noted, a plausible account of these findings follows from the proposal that both source and item memory judgments received support from the recollection of qualitative information about the study episode. Thus, the distinction between the two classes of SME is quantitative rather than qualitative. According to this account, therefore, the finding that source SMEs were only evident in young adults suggests that the memories supporting source judgments in these participants were based on a greater amount of episodic information than were those that supported source judgments in the older group. This proposal is strongly buttressed by the finding, discussed above, that the strength of confident source judgments was markedly higher in the young than in the older age group.

Although parsimonious, the account outlined above does not explain why the cortical source SMEs in the older age group were not only reliably smaller than those in younger adults but undetectable. One possibility is that successful encoding of source as opposed to item information in the young subjects reflected encoding not only of source-specifying information, but of a greater amount of information more generally. This was not the case for the older adults, however. Rather, in this group, whether source or item information was successfully encoded was dictated largely by the nature of the information that was encoded (whether it was diagnostic or non-diagnostic of source). Support for this conjecture comes from the correlations between source and item memory performance in the two age groups: the correlation between pSR and Pr was significantly higher in the young group (rs of 0.76, $p < 0.001$, and 0.35, $p = 0.08$, in the young and older groups respectively; difference, $p = 0.037$). The strong relationship across the young adults between source and item memory performance is consistent with the idea that the information supporting source judgments in this age group was additive with that sufficient to support item memory – that is, items attracting accurate source judgments were a sub-set of those that would have attracted accurate item judgments in the absence of the additional information. The finding that this relationship was markedly weaker within the older group suggests that, in these participants, item judgments that were accompanied by accurate as opposed to inaccurate source judgments were likely based on different classes of episodic information. Whereas the two classes were equally capable of supporting item judgments, they differed in their diagnostic utility for source judgments.

The effects of age on LIFG SMEs were mirrored by the effects in the other 9 cortical regions where SMEs were identified. For the reasons outlined in the Introduction, we directly contrasted the SMEs from the left and right IFG. Consistent with one prior finding (de Chastelaine et al., 2011) but inconsistent with others (de Chastelaine et al., 2016a; Duverne et al., 2009; Morcom et al., 2003), we found no evidence for age-related over-recruitment in the SMEs from the right IFG. Rather, the effects in this region were statistically equivalent to those in the opposite hemisphere. The failure to find an age difference in the magnitude of the RIFG SMEs extends the findings of de Chastelaine et al. (2011) to non-verbal memoranda and indicates that, although frequently reported, age-related enhancement SMEs in the right PFC is by no means ubiquitous.

An important aim of the present study was to examine the relationship between memory performance and SMEs in the left and right IFG. As was detailed in the Introduction, an age-dependent positive relationship between LIFG SMEs and associative recognition performance was reported in two prior studies (de Chastelaine et al., 2011, 2016a), while three prior reports described a negative correlation between memory performance and SMEs in the RIFG (de Chastelaine et al., 2011; Duverne et al., 2009; Miller et al., 2008). Replicating and extending the findings of de Chastelaine et al. (2016a), here we found that, in the older age group, left and right IFG SMEs both demonstrated positive, age-dependent, relationships with memory performance. These findings are consistent with (but not probative of) the proposal of de Chastelaine et al. (2016a) that, when memory representations reflected by RIFG SMEs are accessible on the subsequent memory test, the SMEs will correlate positively with memory performance. For example, it is possible that the employment of pictorial retrieval cues facilitated access to these memory representations. The present findings are also consistent with the same authors’ proposal that with increasing age the IFG becomes a ‘bottleneck’ whose functional integrity plays a role in mediating the efficacy of episodic encoding (see Introduction).

An additional finding from the present study calls into question the specificity of the relationship between IFG SMEs and memory performance, however, in that the SME derived from the 8 extra-IFG cortical regions also demonstrated a robust relationship with performance. Thus, the findings for the IFG appear to reflect a more general relationship between positive cortical SMEs and performance (indeed, in the older group, IFG SMEs and the SME averaged across the extra-IFG cortical regions correlated across participants at $r = 0.716$ and $r = 0.700$ for the left and right IFG respectively, both $p < 0.001$). These findings are reminiscent of those recently reported by Hou et al. (2021a) for the relationship between cortical thickness and cognitive performance (see also Salthouse et al., 2015). These authors reported that right IFG thickness was reliably correlated across participants with a variety of cognitive measures, including a measure of associative recognition performance. Similar correlations with performance were however evident for the mean thickness of the entire right hemisphere, and the relationship between right IFG thickness and memory performance fell short of significance after controlling for the thickness of extra-IFG cortex. These findings do not negate the proposal that increasing age is associated with the emergence of 'bottlenecks' that mediate encoding efficacy. They do suggest however that such bottlenecks are distributed widely throughout the cortex. Certainly, the present findings do not support the contention that the IFG occupies a privileged position in this respect.

Unlike in the cortex, item SMEs in the hippocampus were undetectable despite the presence of highly robust source SMEs. The findings of robust source SMEs in the anterior hippocampus are consistent with prior reports of SMEs in this region (e.g. Becker et al., 2017; de Chastelaine et al., 2011, 2016; Liu et al., 2017; Staresina & Davachi, 2008). The dissociation between item and source (or associative) SMEs, which has been reported previously (Davachi & Wagner, 2002; Chua et al., 2007; Becker et al., 2017), is consistent with the proposal that the hippocampus is engaged specifically in support of 'strong' memories (e.g. Squire et al., 2007; Wais, 2011). It is also consistent with the more nuanced notion that encoding (and retrieval-related) hippocampal fMRI effects are evident only for memories that contain relatively large amounts of contextual information (Rugg et al., 2012; Yu et al., 2012). Either way, the present hippocampal findings represent a dramatic departure from the graded pattern of cortical SMEs observed for the young age group. Consistent with prior findings (e.g. de Chastelaine et al., 2011, 2016a; Duverne et al., 2009; see Maillet & Rajah, 2014 for review), hippocampal source SMEs were age-invariant, with any tendency for an age difference eliminated by controlling for source memory performance.

In a departure from prior findings for associative recognition, when it was reported that hippocampal SMEs demonstrated an age invariant relationship with memory performance (de Chastelaine et al., 2016a), here there was no evidence of a correlation between hippocampal SMEs and subsequent memory performance in the young group. Among the possible reasons for this null finding the most obvious is that it reflects a task difference, such that the magnitude of hippocampal

SMEs in young participants is tied more closely to the accuracy of subsequent associative recognition judgments than it is to subsequent source memory judgments. For example, individual differences in the magnitudes of the source SMEs of the young participants might have reflected not only individual differences in efficacy of encoding source information, but in the encoding of non-criterial or redundant information from the study events also. Evidently, this was not the case for the older adults, for whom there was a sizeable and robust relationship between hippocampal SMEs and subsequent source memory performance.

A reviewer requested that we comment on the implications of our employment of ROIs that were common to the two age groups, rather than using age-specific ROIs. First, as we note in the methods section, the employment of age-independent ROIs minimizes the potential for bias in subsequent analyses. Second, the employment of age-selective ROIs is predicated on the assumption that both age groups will independently demonstrate significant effects in the contrasts of interest, an assumption that is arguably presumptuous. And, as a practical matter, in the present data set we were unable to detect, at the whole brain level, any evidence of regional dissociations in SMEs according to age group.

The present study has some limitations. As remains typical for cognitive neuroscience studies of cognitive aging, it employed a cross-sectional design that precludes the interpretation of the age effects as correlates of aging rather than of age-associated confounding factors such as cohort effects or selection bias (Rugg, 2017). Second, the hemodynamic transfer function mediating between neural activity and the fMRI BOLD signal differs with age (Tsvetanov et al., 2021). Hence, we cannot rule out the possibility that age-related hemodynamic factors played a role in the present findings (although it is hard to envisage how such factors could have impacted the moderating effects of age on brain-behavior relationships). Third, the sample sizes employed in the present study were relatively modest. Therefore, the null findings reported for the effects of age group, memory condition and their interactions should be treated with circumspection until they have been replicated in more highly powered studies.

In conclusion, the findings described above replicate and extend prior studies examining the effects of age on the neural correlates of episodic encoding. Notably, in older adults, the size of SMEs in the hippocampus, the IFG and other cortical regions correlates robustly across participants with their ability to recollect the study items. The findings add to the evidence that the efficacy of the processes supporting the initial encoding of episodic information into memory is a major determinant of memory performance in older adults.

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Declarations of Interest: None

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Robust positive subsequent memory effects (SMEs) were identified in the IFG in each age group, with both source and item effects in the young group but an item effect only in the older group.

Positive SMEs in a further 8 cortical regions demonstrated the same pattern as in the IFG.

Hippocampal SMEs exclusively predicted source memory, and the magnitude of these effects did not reliably differ between the age groups.

In the older group only, positive relationships were identified between memory performance and SMEs in the left IFG, hippocampus, and extra-IFG cortical regions.