Age differences in hippocampal activation during gist-based false recognition

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ABSTRACT

Age-related increases in reliance on gist-based processes can cause increased false recognition. Understanding the neural basis for this increase helps to elucidate a mechanism underlying this vulnerability in memory. We assessed age differences in gist-based false memory by increasing image set size at encoding, thereby increasing the rate of false alarms. False alarms during a recognition test elicited increased hippocampal activity for older adults as compared to younger adults for the small set sizes, whereas the age groups had similar hippocampal activation for items associated with larger set sizes. Interestingly, younger adults had stronger connectivity between the hippocampus and posterior temporal regions relative to older adults during false alarms for items associated with large versus small set sizes. With increased gist, younger adults might rely more on additional processes (e.g., semantic associations) during recognition than older adults. Parametric modulation revealed that younger adults had increased anterior cingulate activity than older adults with decreasing set size, perhaps indicating difficulty in using monitoring processes in error-prone situations.

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1. Introduction

Prior research has shown that older adults have difficulty remembering previous events as well as younger adults (Light, 1991). This age-related difference is likely the result of deficits in recollection for specific contextual details, whereas familiarity-based recognition remains intact with age (e.g., Spencer and Raz, 1995; Yonelinas, 2002). Extant work suggests that encoding engenders 2 types of memory traces: verbatim and gist traces (Brainerd and Reyna, 1990). Verbatim traces contain the distinctive details of an event, whereas gist traces retain the general meaning of the event without specific perceptual details (Brainerd and Reyna, 1990). False memories typically occur when the gist trace is retrieved, and no verbatim trace is accessible. Consistent with this notion, age-related increases in false memories are most robust when old and new information share common semantic or perceptual characteristics (Balota et al., 1999; Kensinger and Schacter, 1999; Koutstaal and Schacter, 1997; Norman and Schacter, 1997).

Although reliance on gist processing has been shown to vary by task demands among younger adults (Loftus et al., 1995; Roediger and McDermott, 1995; Schacter, 1999, 2008), aging increases the use of gist, resulting in poor memory in older adults when recollection requires remembering specific details (Brainerd and Reyna, 2002; Tun et al., 1998). Identifying mechanisms underlying age differences in false recognition that result from gist-based processing is important for understanding how to reduce vulnerability to such errors, especially given a shift toward greater reliance on gist-based memory processes with age (Koutstaal and Schacter, 1997). The present study employed neuroimaging to elucidate a neural mechanism for age differences in false memory at retrieval that results from gist-based processing.

Extant neuroimaging research has revealed age differences in activation relative to verbatim versus gist retrieval. Regions including the hippocampus, early visual cortex, lateral parietal cortex, occipitoparietal cortex, and rhinal cortex are involved at retrieval, although their roles depend on the processes required, namely recollection versus familiarity. At retrieval, these regions associated with recollection (e.g., the hippocampus, early visual cortex, and lateral parietal cortex) show age-related deficits in activation (Ally et al., 2008; Daselaar et al., 2006; Duarte et al., 2008). However, regions implicated in familiarity (e.g., rhinal cortex, occipitoparietal cortex) show intact or often enhanced

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functioning with age (Daselaar et al., 2006; Dennis et al., 2008b; Duarte et al., 2010). This work evidences that older adults typically show significant reductions in true recollection (Bastin and Van der Linden, 2003; Davidson and Glisky, 2002), whereas familiarity processes remain preserved throughout the lifespan (Bastin and Van der Linden, 2003; Naveh-Benjamin, 2000).

In memory, hippocampal activation contributes to binding details during encoding and reconstructing them during retrieval (Yassa et al., 2011). In younger adults, the hippocampus can be differentially activated on a within-subject basis by varying the amount of to-be-remembered information. For example, set size of information at encoding (i.e., manipulating the number of object exemplars at encoding to evoke more gist-based processing) is positively associated with both false alarm rates and increased hippocampal activity at retrieval in younger adults (Gutchess and Schacter, 2012). Increased hippocampal activity for larger set sizes suggests that features shared by target and lure items elicit similar reconstructive processes that ultimately lead to false memories.

Among older adults, the role of the hippocampus in gist processing at retrieval may be responsible for eliciting errors in several ways. First, older adults may have difficulty monitoring retrieval attempts (e.g., Fandakova et al., 2013a, 2013b). In this case, the hippocampus may fail to access the correct information, possibly due to a failure in binding the details together (Naveh-Benjamin, 2000). Here, decreased hippocampal activity would reflect deficient processing in which original encoding information is not properly reactivated. However, increased hippocampal engagement may lead to reactivation failure if this engagement corresponds with the number of reactivated features. In this case, older adults may retrieve more information by activating irrelevant features, ultimately eliciting more incorrect bindings.

Second, hippocampal activation may also play a role in false recognition with regard to gist processing through pattern separation. Aging diminishes the capacity to separate new information from similar inputs that could cause interference (pattern separation), leading to an increase in the retrieval of previous information from a partial cue (pattern completion) (Yassa and Stark, 2011). True recollection requires memories to be unique enough from other interfering information, relying on pattern separation (Norman, 2010). The more interference from overlapping events that needs to be overcome, the more separation becomes critical for recollection to occur (Yassa and Stark, 2011). Prior work in both rodents (e.g., Wilson et al., 2006) and humans (e.g., Stark et al., 2010; Yassa et al., 2010) suggests that false memories elicited through deficient pattern separation occurs specifically in the dentate gyrus and is coupled with pattern completion in older adults. In this case, the hippocampus responds to the novelty of information, with decreased activation suggesting impaired pattern separation abilities (Duncan et al., 2012; Fandakova et al., 2013a; Kumaran and Maguire, 2006). With regard to the present work, we hypothesized that decreased hippocampal activation would occur concomitantly with increased false alarms, due to age-related differences in the ability to differentiate target from novel stimuli. This may potentially result from deficits in pattern separation ability.

In the present study, we analyzed younger and older adults' neural activity when recognizing novel exemplars taken from small, medium, or large set sizes of objects drawn from the same category (e.g., bicycles). This manipulation varied the level of gist associated with each category. Younger adults employ reconstructive processes as shown with increases in hippocampal activation during gist-related false recognition (Gutchess and Schacter, 2012). Given declines in hippocampal activation with age (Fandakova et al., 2013a; Naveh-Benjamin, 2000), we anticipated reduced hippocampal activity in younger versus older adults, suggestive of a shift toward gist-based processing, and induced through the use of large versus small set sizes. However, although we expected hippocampal engagement to change with age due to gist, this could be reflected through several patterns of neural activity. Whether hippocampal activation tracks the level of gist to a lesser degree for older versus younger adults, or does not respond to manipulation of gist at all in older adults, is an open question addressed through this work.

Due to age-related differences in the ability to differentiate target from novel stimuli, older adults may instead draw on other processes to help memory performance. One possibility is that given age-related deficits in pattern separation (Duncan et al., 2012; Fandakova et al., 2013a; Kumaran and Maguire, 2006), older adults may recruit regions implicated in semantic processes during retrieval (Dennis et al., 2007, 2008a). We thereby predicted that older versus younger adults would activate more lateral temporal regions associated with semantic processing for large versus small set sizes. These predictions coalesce with patterns found in prior aging research at retrieval using both verbal (Dennis et al., 2008b) and visual (Koutstaal and Schacter, 1997) stimuli. The present study extends this work by further manipulating gist in a graded fashion for visual stimuli sharing perceptual as well as semantic properties to investigate how gist reliance influences age differences in the neural correlates of false memory at retrieval.

Beyond assessing age differences in activity related to gist-based processing and consequent false memory in isolated regions, we tested how hippocampal connectivity changes with age given different levels of gist contributing to false memories. Age-related decreases in connectivity between the hippocampus and posterior temporal regions underlie memory deficits in aging, and specifically, increases in false memories (Dennis et al., 2008b). Despite reduced connectivity between the hippocampus with posterior regions, however, enhanced hippocampal connectivity with frontal regions at encoding predicts better memory performance for older adults (Daselaar et al., 2006; Dennis et al., 2008a). Hippocampal-frontal cortex connectivity suggests that older adults compensate for deficits in posterior connectivity by relying on frontal top-down modulation (Daselaar et al., 2006; Dennis et al., 2008a; Grady et al., 2003). However, little research has considered age-related functional connectivity changes between the hippocampus and these regions during false recognition for items that vary in gist. For large versus small set sizes, we predicted that younger adults would have greater connectivity relative to older adults from the hippocampus to regions involved in perceptual processes. Although older adults may exhibit increased activation in inferior temporal regions during false recognition (Daselaar et al., 2006), the connectivity between these regions and the hippocampus may be weakened with age (Dennis et al., 2008b). Concomitant with age-related reductions in posterior connectivity, we predicted that older adults would have greater connectivity with frontal regions, a pattern suggested to reflect strategic shifts to support task performance (Davis et al., 2008). Further we predicted that connectivity would be greater for large relative to small set sizes due to the heavy reliance on gist-based processing.

Finally, we conducted a parametric modulation analysis to capitalize on our graded levels of gist, allowing us to assess age-related changes in neural activity corresponding to increasing or decreasing levels of gist that are associated with varying levels of false memory. Beyond the hippocampus, we identified lateral temporal cortex as a candidate region whose activity may be modulated by the extent of gist-based processing, given its involvement in semantic processing. Extant work has shown age differences in reliance on semantic processes with increased activation in the lateral temporal cortex for older adults at retrieval (Davis et al., 2008; Dennis et al., 2008a). We predicted that with increasing set size (i.e., small, medium, and large), older adults

would show increased reliance on semantic processes, reflected in increased lateral temporal cortex activation. These analyses can help distinguish the potential roles of the hippocampus and lateral temporal cortex in gist-based memory errors.

2. Method

2.1. Participants

Sixteen younger (mean age = 24.13 years, SD = 4.57; 8 male; age range = 19–33 years) and 16 older (mean age = 71.81 years, SD = 5.58; 7 male; age range = 61–80 years) adults participated. An additional 7 younger adults and 3 older adults were excluded due to failure to respond to large numbers of trials (>40% no responses; 1 younger adult, 1 older adult), failure to follow instructions (1 younger adult), too few false alarms in at least 1 condition (<6 items; 5 younger adults), or excessive movement in the scanner (2 older adults). Participants were right-handed, native English speakers with no usage of medications known to affect the central nervous system, and no neurological, psychological, or physical conditions that were problematic for magnetic resonance imaging (MRI) scanning. Education levels were similar for younger (mean = 16.41 years, SD = 2.85) and older (mean = 15.00 years, SD = 2.03) adults, $t(30) = 1.61$, $p = 0.12$. Younger adults (mean = 79.44, SD = 13.29) had increased processing speed than older adults (mean = 54.56, SD = 10.45), $t(30) = 5.89$, $p < 0.001$, as measured by digit comparison (Hedden et al., 2002). Participants provided written informed consent. The Harvard University and Partners Institutional Review Boards approved this study.

2.2. Materials and Procedure

468 pictures of single objects were incidentally encoded by participants, who were unaware there would be a future recognition test. Participants made yes or no decisions via a button box about whether each object was something they would use or interact with during an average day. Pictures were selected from photo CDs (Hemera Technologies, Gatineau, Quebec) to include 54 sets of categorized objects (e.g., umbrellas, chairs, cats). Eighteen categories were assigned to each condition (small, medium, or large set size). The number of object exemplars in each category determined set size. Small study sets contained 4 studied exemplars (e.g., 4 umbrellas). Medium sets contained 8 studied exemplars (e.g., 8 chairs). Large sets contained 14 exemplars (e.g., 14 cats). Exemplars were distributed across 3 encoding runs (e.g., the 8 chairs would be distributed as evenly as possible across the 3 runs), with each run lasting approximately 7 minutes. Across the 3 encoding runs, participants viewed 72 pictures from small sets, 144 pictures from medium sets, and 252 pictures from large sets (see Fig. 1). Each picture was presented for 1 second followed by a 1 second blank interval. All stimuli were presented via E-Prime (Psychology Software Tools, Pittsburgh, PA, USA). Trials were randomly ordered through a jittered event-related design (Dale, 1999) with a fixation cross appearing for times varying from 2000 to 10,000 ms throughout the scans (for results at encoding, see Gutchess and Schacter, 2012).

After an approximately 10-minute delay, during which structural images were acquired, participants received a surprise recognition test over 4 functional scans. The recognition test included a total of 456 pictures (216 studied and 240 lures). Each studied small, medium, and large object category (e.g., chairs) was tested with 4 studied exemplars and 4 novel lure exemplars, both randomly selected from the studied and unstudied items for each category (see Fig. 1). Therefore, there were a total of 72 items in each of the conditions (small, medium, large set size) evenly distributed across 4 runs, with each run approximately 10 minutes long. To determine a baseline false alarm rate, an additional 24 novel-unrelated pictures were included from distinct object classes not previously studied. Eight different recognition orders across participants counterbalanced the assignment of object classes to
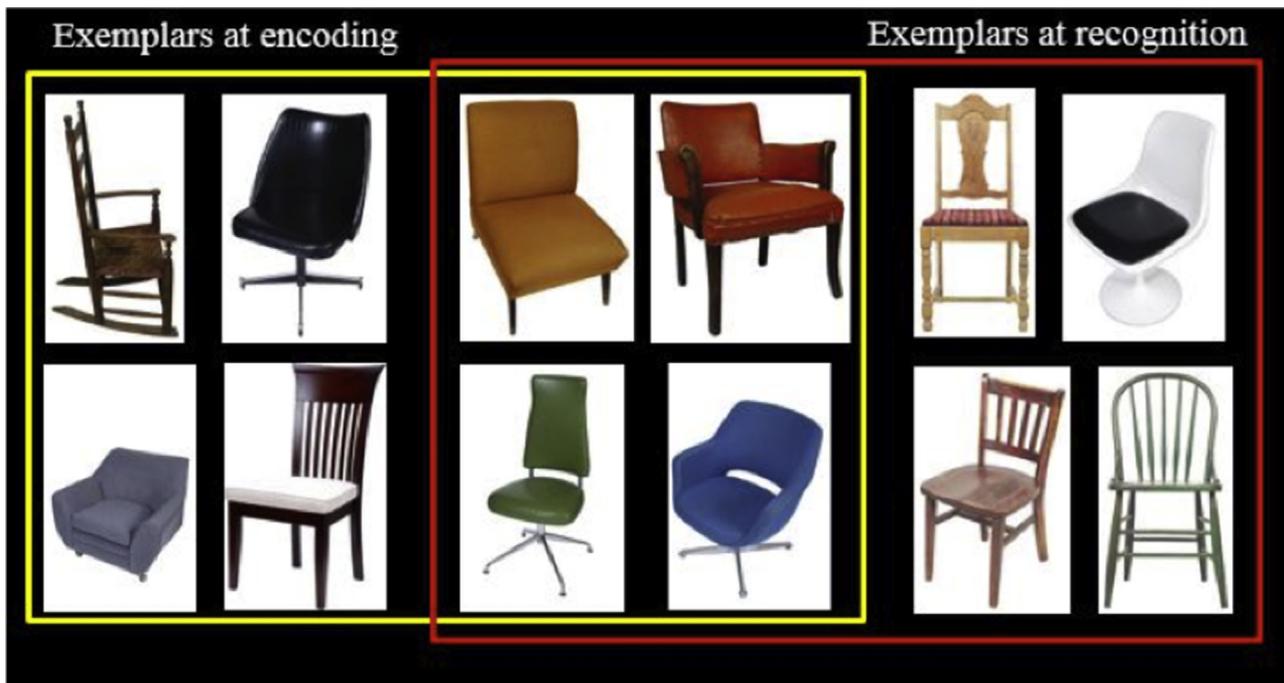

Fig. 1. In the task, participants incidentally encoded 468 pictures of single objects (as shown on the left). The number of object exemplars in each category determined its set size. After a delay, participants completed a recognition test that included a total of 456 pictures (216 studied and 240 lures). Each studied small, medium, and large object category (e.g., chairs) was tested with 4 studied exemplars and 4 novel lure exemplars (as shown on the right), both randomly selected from the studied and unstudied items for each category. An additional 24 novel-unrelated pictures were included from distinct object classes not previously studied.

each of the 4 set sizes (i.e., unrelated, small, medium, and large) and assignment of tested items as either lures or studied targets. Participants had a 4-second interval to respond "yes" (i.e., had seen the exemplar before) or "no" (i.e., had not seen the exemplar before).

2.3. Functional MRI data acquisition

Images were acquired using a Siemens Avanto 1.5 Tesla whole-body scanner. Thirty-two slices 3.2-mm thick with a 0.3-mm skip were acquired with an echo-planar imaging sequence (repetition time = 2000 ms, echo time = 30, field of view = 200 mm, and a flip angle of 90°). In each of the 3 encoding runs, 212 volumes were collected; in each of the 4 recognition runs, 304 volumes were collected. Besides the number of volumes collected, all other parameters were the same for both encoding and recognition.

2.4. Functional MRI analyses

2.4.1. General linear model

Preprocessing and analyses were conducted in statistical parametric mapping (SPM) 8 (Wellcome Department of Cognition Neurology, London, UK). Images were slice-time corrected, realigned to correct for motion, normalized to the Montreal Neurological Institute (MNI) template, and smoothed using an 8-mm full width half maximum isotropic Gaussian kernel. Estimates of canonical hemodynamic responses were included for each participant in a whole-brain random effect analysis, used to assess age differences in brain activation. We included 8 regressors in a first-level model: false alarms (FA)-large, FA-medium, FA-small, hits-large, hits-medium, hits-small, zero-correct rejections (novel lures), and miscellaneous (i.e., all misses and remaining correct rejections, false alarms to the zero category, and nonresponse trials). We separated correct rejections into 2 different regressors, as items that have not been seen previously may rely on gist processing (e.g., I did not see any bicycles), whereas items from categories previously presented (novel lures) may rely on detail-specific recollection. Behavioral false-alarm estimates for each participant were included in a group level analysis, treating participants as a random effect. A 2 (age group: younger, older) × 2 (set size: small, large) analysis of variance (ANOVA) model was created to explore any effects of set size during false recognition differing by age group. FMRI results were thresholded at $p < 0.001$ with an extent threshold of $k = 5$ voxels, parameters widely used in aging-related neuroimaging work (Duarte et al., 2008; Dulas and Duarte, 2012; Kensinger and Schacter, 2008). Peak activations on the cortical surface were determined using SPM8 and Brodmann areas labeled with MRIcron (Rorden and Brett, 2000). Based on the whole-brain analysis, we characterized activity in a priori regions of interest (e.g., hippocampus) by extracting parameter estimates from significant clusters and plotting them, where relevant. To specifically address our hypothesis regarding age differences in brain activity during false recognition of objects in large versus small set sizes, we created the following interaction contrasts: (young > old for [large > small]), (old > young for [large > small]). We compared small and large set sizes given that it would be the most robust analysis to detect age-related differences in hippocampal activation to gist-based false recognition based on our predictions.

2.4.2. Functional connectivity

Psychophysiological interactions (PPIs) assess task-dependent functional connectivity analyses for a seed region. Functional connectivity evaluates how activity in a given region covaries with activity in other areas of the brain when comparing across conditions (e.g., in the present study, hippocampal activity during false alarms to large set size versus false alarms to small set size) (Friston et al., 1997). For our analysis, we used the gPPI toolbox, which accommodates more than 2 task conditions in the same PPI and has been argued to be more sensitive than standard PPI implementation through SPM (McLaren et al., 2012). In this follow-up analysis, we used the left hippocampus region identified by our whole brain general linear model analysis (see Section 3) as a seed region to examine age differences in connectivity with the hippocampus when making false alarms to items from large versus small set sizes, as this constitutes the most extreme comparison across levels of gist. We extracted the deconvolved time series from a 6-mm radius sphere around the group peak by testing the connectivity for false alarms to large versus small set size items. We entered the contrast files from participant-level PPI analyses into a 2-sample t-test, comparing connectivity from the hippocampal seed between younger and older adults in the comparison of large versus small set size false alarms.

2.4.3. Parametric modulation

Parametric modulation analyses allowed for identification of regions whose activity increases or decreases as a function of gist-based false memories. That is, this analysis revealed neural activity varying with increasing or decreasing set size. Unlike the previous first-level model (see Section 2.4.1), the parametric modulation model used FA-set size (i.e., small, medium, and large) as a covariate of interest to identify neural regions whose activation tracks across the 3 levels of set size during false recognition responses. Like the previous analysis (see Section 2.4.1), we included hits, zero-correct rejections (novel lures), and miscellaneous (i.e., all misses and remaining correct rejections, false alarms to the zero category, and nonresponse trials) in this model. These analyses identified regions whose activity positively or negatively correlated with increasing or decreasing set size for false recognition responses. To identify any age differences in how brain regions track set size during false recognition, we submitted best-fit first-level components to second-level 2-sample t-tests comparing younger to older adults, and older to younger adults.

3. Results

3.1. Behavioral data

We assessed age differences in false recognition by entering false alarm rates into a 2 (age: young, old) × 3 (set size: small, medium, large) mixed ANOVA (See Table 1). Older adults had higher false recognition rates (mean = 0.32, SD = 0.10) than younger adults (mean = 0.24, SD = 0.10), $F(1,30) = 4.70$, $p = 0.04$, partial $\eta^2 = 0.14$. A main effect of set size emerged, $F(2, 60) = 42.66$, $p < 0.001$, partial $\eta^2 = 0.59$. Across age, false alarm rate was greater for the large set size (mean = 0.34, SD = 0.12) versus medium (mean = 0.28, SD = 0.12), $t(31) = 4.31$, $p < 0.001$, and for the medium set size versus the small (mean = 0.22, SD = 0.10), $t(31) = 5.67$, $p < 0.001$. No interaction emerged, $p = 0.20$. Because several younger adults (N = 5)

Table 1
Behavioral data for false alarms and hits

Set size	Old	Young
False alarms		
Small	0.24 (0.11)	0.19 (0.09)
Medium	0.33 (0.10)	0.24 (0.13)
Large	0.39 (0.12)	0.30 (0.10)
Hits		
Small	0.59 (0.14)	0.60 (0.14)
Medium	0.62 (0.14)	0.63 (0.15)
Large	0.65 (0.14)	0.63 (0.12)

were excluded for having too few false alarm trials, the behavioral data from the participants included in the fMRI analyses may underestimate potential age differences (see Bastin and Van der Linden, 2003; Davidson and Glisky, 2002; Naveh-Benjamin, 2000 for more thorough consideration of the effects of aging) in false alarm rates across the set sizes. When the ANOVA is conducted with all participants who completed the study, an age by set size interaction emerged, $F(2,78) = 4.951$, $p = 0.01$, partial $\eta^2 = 0.11$, consistent with prior behavioral literature.

Although not our primary interest, behavioral hit rate was also analyzed in a 2 (age: young, old) × 3 (set size: small, medium, large) mixed ANOVA to determine age-related differences in correct responses to old items (See Table 1). Older adults did not differ from younger adults on hit rate, $F(1,30) = 0.005$, $p = 0.94$, partial $\eta^2 < 0.01$. A main effect of set size emerged, $F(2,60) = 4.27$, $p = 0.018$,

partial $\eta^2 = 0.13$. Hit rate was not greater at the large set size (mean = 0.64, SD = 0.13) versus medium (mean = 0.62, SD = 0.14), $t(31) = 0.98$, $p = 0.33$ but was greater for the large set size versus the small (mean = 0.59, SD = 0.14), $t(31) = 2.95$ $p = 0.006$. Hit rate at the medium set size was marginally greater than the small, $t(31) = 1.84$, $p = 0.08$. No interaction emerged, $p = 0.70$.

3.2. Functional MRI data

3.2.1. Age by set size interaction

([young > old] for [large > small]). Comparing age differences in brain activity for false alarm responses for large versus small set sizes revealed a singular activation in the left hippocampus (Fig. 2A; $k = 9$; MNI coordinates: −30, −18, −18). To characterize the pattern of the age differences in this interaction, we entered and compared
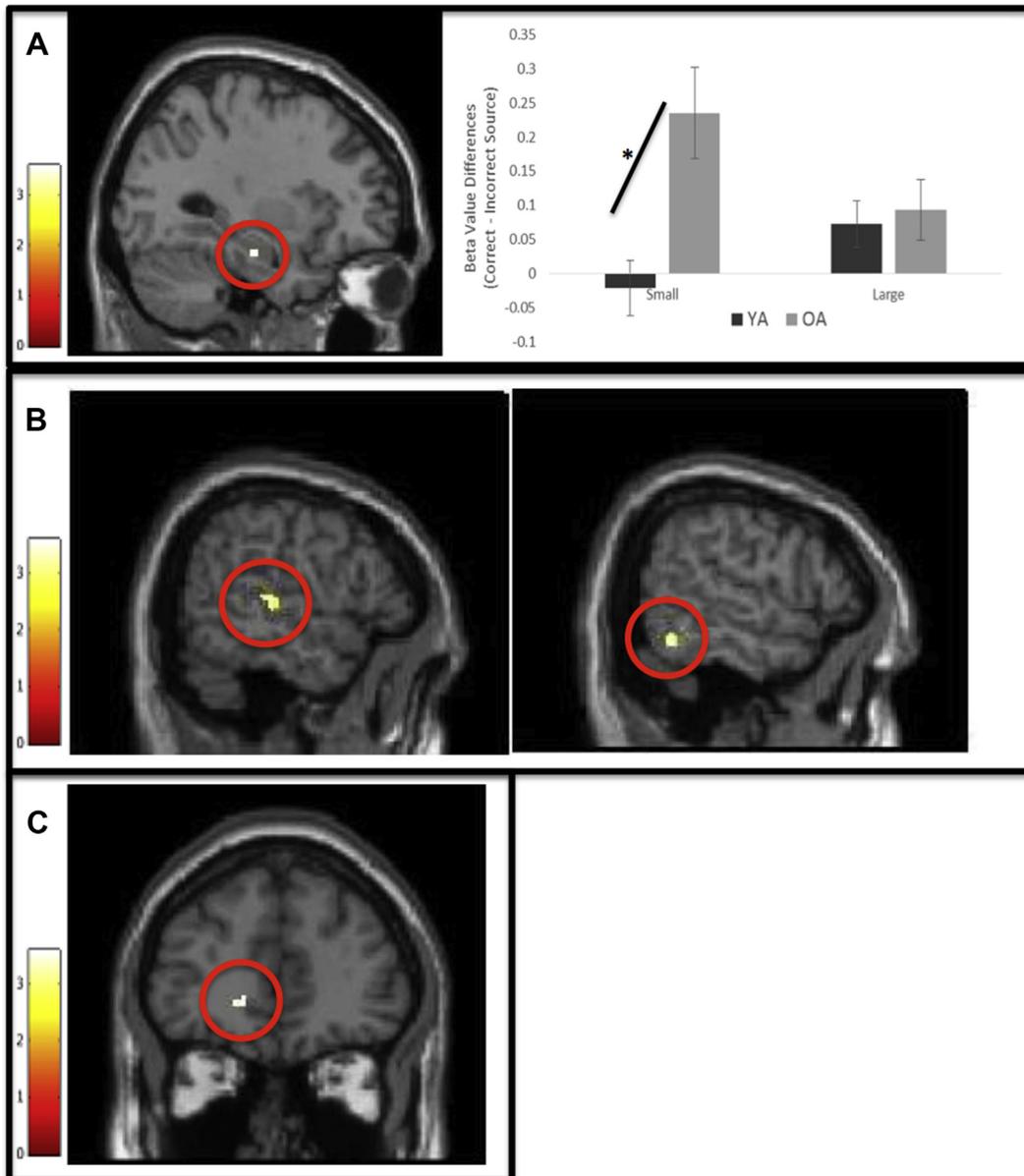

Fig. 2. (A) A region in left hippocampus emerged when comparing age differences in activity for false recognition at the large versus small set size (left). Plotting parameter estimates to characterize this activation revealed the interaction to be driven by more activity among older adults versus young at the small set size, with no age difference at the large set size (right). (B) At the large versus small set size, younger adults exhibited increased functional connectivity between the left hippocampus and the left superior temporal cortex (left) and the right inferior temporal cortex (right) relative to older adults. (C) When examining decreasing set size (i.e., large to medium to small exemplars) in a parametric modulation analysis, younger adults showed increased left anterior cingulate cortex activity relative to older adults. Abbreviations: OA, older adult; YA, younger adult. *Significant at $p = 0.003$.

parameter estimates from this hippocampal region in a 2 (age group: young, old) × 2 (set size: small, large) mixed ANOVA. This revealed a significant set size × age group interaction, $F(1, 30) = 10.46$, $p = 0.003$, partial $\eta^2 = 0.26$. Older adults recruited left hippocampus more than young when set size was small, $t(30) = 3.26$, $p = 0.003$, $d = 1.15$. No age differences emerged when set size was large, $t(30) = 0.38$, $p = 0.71$, $d = 0.13$. No other regions emerged from this interaction contrast or from comparing ([old > young] for [large > small]).

3.2.2. Functional connectivity

Consistent with our predictions, at the large versus small set size, younger adults showed greater functional connectivity between the hippocampus and temporal regions than older adults. Specifically, relative to older adults, younger adults had greater functional connectivity between the left hippocampus (MNI coordinates: −30, −18, −18) and right inferior temporal cortex ($k = 21$; BA 37, MNI coordinates: 60, −50, −16), as well as with left superior temporal cortex ($k = 21$; BA 22, MNI coordinates: −54, −26, 6; Fig. 2B). No regions emerged as greater for older adults than younger adults for the large versus small set size.

3.2.3. Parametric modulation

For false recognition, decreasing set size (i.e., large, medium, and small exemplars studied) was associated with increased activation in a singular region of left anterior cingulate gyrus (BA 24; $k = 5$; MNI coordinates: −14, 42, 0) for younger relative to older adults (Fig. 2C). No other age differences emerged for decreasing set size, and no age differences emerged for increasing set size.

4. Discussion

The present study investigated the neural underpinnings of how increased use of gist-based processing affects false memory for visual stimuli in aging. We had predicted involvement of the hippocampus, as previous work has suggested that the more closely items are related (e.g., items that share the same verbal label), the more processes involved in false recognition are activated (Koutstaal and Schacter, 1997). This yields a greater need for hippocampal-based reconstruction as the degree of gist increases for false memories in younger adults (Gutchess and Schacter, 2012). However, the pattern is far less clear for older adults who have been shown to consistently rely on gist-memory (Tun et al., 1998). In the present study, older adults exhibited increased hippocampal activation for false memories for items at the small set size relative to younger adults. Initially, we had predicted that older adults would show less hippocampal activation relative to younger adults and given that reliance on gist should increase with set size. This difference would be more prominent at the large set size. However, we observed an unexpected pattern such that older adults tend to activate the hippocampus more for the small set size, which leads to age differences in this condition. In contrast, hippocampal activity was equivalent at the large set size between younger and older adults, reflecting a tendency for older adults to activate the region less for large than small set sizes. No other age differences emerged from the random effects analyses.

Age-related differences in hippocampal activation between the small and large set size may potentially reflect deficits in pattern separation ability. Increased age corresponds with a reduced capacity to separate new information from related inputs causing interference (pattern separation) and an increased tendency to retrieve related information from a partial cue (pattern completion) (Yassa and Stark, 2011). For true recollection to occur, memory traces for information must be unique enough compared with other interfering information, thus requiring pattern separation (Norman,

2010). The more information overlaps causing interference, the more separation becomes critical (Yassa and Stark, 2011). In the present task, participants had to retrieve information that was tightly connected with other information (e.g., exemplars in an object category). For older adults at the small set size, increased activation in the hippocampus relative to younger adults may suggest effortful retrieval. However, at the large set size, equivalent hippocampal activation between younger and older adults suggests deficient pattern separation (i.e., too much interference to resolve) and a shift toward pattern completion (i.e., retrieving the gist of the information) (e.g., Stark et al., 2010; Yassa et al., 2010). In this case, the hippocampus works to detect novelty of information at the small set size, but at the large set size there is too much information to separate (Duncan et al., 2012; Fandakova et al., 2013a; Kumaran and Maguire, 2006).

These findings may also be interpreted using the scaffolding theory of aging and cognition (STAC). STAC posits that the brain adapts with age to engage in compensatory "scaffolding" in response to challenges as a result of declining neural structure and function (Park and Reuter-Lorenz, 2009; Reuter-Lorenz and Park, 2014). STAC suggests that despite neural changes, behavior can be maintained with age due to the engagement of compensatory scaffolding. Scaffolding processes may operate on a lesser scale in youth, only engaged in novel situations, new learning, or neural challenges (Park and Reuter-Lorenz, 2009). With increased age, in contrast, scaffolding processes may be engaged even for familiar tasks or basic cognitive operations as these become more difficult with degradation of previous neural circuitry (Park and Reuter-Lorenz, 2009). For older adults to have increased hippocampal activation at the small set size relative to younger adults, this suggests that compensatory recollection responses (e.g., by way of pattern separation) are engaged for older adults. However, large set sizes might exceed older adults' capacity to counteract gist-based false memories, and they are unable to harness additional resources to support performance, making younger and older adults comparable in hippocampal activation. The equivalent hippocampal response for younger and older adults at large set sizes may reflect both extrinsic challenge (e.g., higher task demand in younger adults at the large set size) and intrinsic challenge (e.g., aging brain) at the large set size.

Because greater hippocampal activation for older adults relative to young adults at the small set size does not clearly delineate the processes engaged differently across the age groups as gist increases, we assessed how functional connectivity differs across set size with age. With regard to STAC, it is possible that beyond the small set size, older adults are relying on activation in secondary scaffolded areas (Park and Reuter-Lorenz, 2009). We thus sought to identify connections potentially involved as a function of greater gist processing. Connections between the hippocampus and both the right inferior and left superior temporal cortex were greater for younger adults relative to older adults for the large versus small set size. Consistent with these findings, previous memory work has revealed an age-related decrease in connectivity between the hippocampus and posterior regions, such as the parietotemporal network, at encoding (Daselaar et al., 2006; Dennis et al., 2008a). Prior work manipulating gist information in younger adults has shown that semantic processing is involved in this type of graded visual task using gist-processing (Gutchess and Schacter, 2012), potentially suggesting that these age-related changes in functional connectivity reflect the contribution of semantic processes. As the amount of gist increases (such as in the large set size), younger adults may compensate via greater functional connectivity with regions associated with semantic processes (Daselaar et al., 2006).

Extant work has also suggested an age-related decrease in inferior temporal activity (Davis et al., 2008) and connectivity

suggesting older adults are less efficient at these processes (Dennis et al., 2008a). However, we did not find support for our hypothesis that older adults may compensate for weaker posterior connectivity with increased connectivity between the hippocampus and frontal cortex. This prediction is based on prior work suggesting that this pattern predicts better subsequent memory performance (Daselaar et al., 2006; Dennis et al., 2008a; Grady et al., 2003). This could suggest that prior findings from work on correct recognition may not extend to false recognition.

Interestingly, anterior cingulate cortex increased in activity with decreasing set size for younger adults more than older adults. Prior work has shown that true recognition is associated with increased engagement of visual, posterior parietal, and temporal cortex, suggesting reactivation of sensory information, whereas false recognition is associated with engagement of the frontal cortex, specifically the anterior cingulate, representative of monitoring of retrieved memories (Cabeza et al., 2001). Anterior cingulate is engaged during both correct and incorrect responses, suggesting its involvement in situations where errors are likely to occur rather than solely during specific errors (Carter et al., 1998). In contrast to younger adults, older adults do not differentially recruit anterior cingulate to assess salient categorical differences in unrelated items, suggesting age-related deficits in using specific details to assess novelty (Bowman and Dennis, 2015). In the present data, anterior cingulate activity increased as set size decreased. A possible explanation is that older adults did not differentially recruit the anterior cingulate to distinguish salient differences in novel items, whereas younger adults were able to use this monitoring when there was less gist information.

5. Conclusions

This research extends prior gist and false memory research by investigating neural age differences in false memories for graded gist information. Our results suggest that hippocampal involvement extends to visual stimuli in regards to false memory and gist. That younger adults exhibited enhanced connectivity with inferior and superior temporal regions relative to older adults at the large versus small set size suggests that younger versus older adults use additional resources (e.g., semantic processes) to distinguish between old and new information when the level of gist is greater. Age-related increases in gist-based processes may result from deficits in hippocampal activation, affecting capabilities such as pattern separation, and impaired connectivity with semantic regions.

Disclosure statement

The authors have no conflicts of interest to disclose.

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References

Ally, B.A., Waring, J.D., Beth, E.H., McKeever, J.D., Milberg, W.P., Budson, A.E., 2008. Aging memory for pictures: using high-density event-related potentials to understand the effect of aging on the picture superiority effect. Neuropsychologia 46, 679–689.

Balota, D.A., Cortese, M.J., Duchek, J.M., Adams, D., Roediger III, H.L., McDermott, K.B., Yerys, B.E., 1999. Veridical and false memories in healthy older adults and in dementia of the Alzheimer's type. Cogn. Neuropsychol. 16, 361–384.

Bastin, C., Van der Linden, M., 2003. The contribution of recollection and familiarity to recognition memory: a study of the effects of test format and aging. Neuropsychology 17, 14.

Bowman, C.R., Dennis, N.A., 2015. Age differences in the neural correlates of novelty processing: the effects of item-relatedness. Brain Res. 1612, 2–15.

Brainerd, C.J., Reyna, V.F., 1990. Gist is the grist: fuzzy-trace theory and the new intuitionism. Dev. Rev. 10, 3–47.

Brainerd, C.J., Reyna, V.F., 2002. Fuzzy-trace theory and false memory. Curr. Dir. Psychol. Sci. 11, 164–169.

Cabeza, R., Rao, S.M., Wagner, A.D., Mayer, A.R., Schacter, D.L., 2001. Can medial temporal lobe regions distinguish true from false? an event-related functional MRI study of veridical and illusory recognition memory. Proc. Natl. Acad. Sci. 98, 4805–4810.

Carter, C.S., Braver, T.S., Barch, D.M., Botvinick, M.M., Noll, D., Cohen, J.D., 1998. Anterior cingulate cortex, error detection, and the online monitoring of performance. Science 280, 747–749.

Dale, A.M., 1999. Optimal experimental design for event-related fMRI. Hum. Brain Mapp. 8, 109–114.

Daselaar, S.M., Fleck, M.S., Dobbins, I.G., Madden, D.J., Cabeza, R., 2006. Effects of healthy aging on hippocampal and rhinal memory functions: an event-related fMRI study. Cereb. Cortex 16, 1771–1782.

Davidson, P.S., Glisky, E.L., 2002. Neuropsychological correlates of recollection and familiarity in normal aging. Cogn. Affect. Behav. Neurosci. 2, 174–186.

Davis, S.W., Dennis, N.A., Daselaar, S.M., Fleck, M.S., Cabeza, R., 2008. Que PASA? the posterior-anterior shift in aging. Cereb. Cortex 18, 1201–1209.

Dennis, N.A., Hayes, S.M., Prince, S.E., Madden, D.J., Huettel, S.A., Cabeza, R., 2008a. Effects of aging on the neural correlates of successful item and source memory encoding. J. Exp. Psychol. Learn. Mem. Cogn. 34, 791.

Dennis, N.A., Kim, H., Cabeza, R., 2007. Effects of aging on true and false memory formation: an fMRI study. Neuropsychologia 45, 3157–3166.

Dennis, N.A., Kim, H., Cabeza, R., 2008b. Age-related differences in brain activity during true and false memory retrieval. J. Cogn. Neurosci. 20, 1390–1402.

Duarte, A., Graham, K.S., Henson, R.N., 2010. Age-related changes in neural activity associated with familiarity, recollection and false recognition. Neurobiol. Aging 31, 1814–1830.

Duarte, A., Henson, R.N., Graham, K.S., 2008. The effects of aging on the neural correlates of subjective and objective recollection. Cereb. Cortex 18, 2169–2180.

Dulas, M.R., Duarte, A., 2012. The effects of aging on material-independent and material-dependent neural correlates of source memory retrieval. Cereb. Cortex 22, 37–50.

Duncan, K., Ketz, N., Inati, S.J., Davachi, L., 2012. Evidence for area CA1 as a match/mismatch detector: a high-resolution fMRI study of the human hippocampus. Hippocampus 22, 389–398.

Fandakova, Y., Shing, Y.L., Lindenberger, U., 2013a. Differences in binding and monitoring mechanisms contribute to lifespan age differences in false memory. Dev. Psychol. 49, 1822.

Fandakova, Y., Shing, Y.L., Lindenberger, U., 2013b. High-confidence memory errors in old age: the roles of monitoring and binding processes. Memory 21, 732–750.

Friston, K., Buechel, C., Fink, G., Morris, J., Rolls, E., Dolan, R., 1997. Psychophysiological and modulatory interactions in neuroimaging. Neuroimage 6, 218–229.

Grady, C.L., McIntosh, A.R., Craik, F.I., 2003. Age-related differences in the functional connectivity of the hippocampus during memory encoding. Hippocampus 13, 572–586.

Gutchess, A.H., Schacter, D.L., 2012. The neural correlates of gist-based true and false recognition. Neuroimage 59, 3418–3426.

Hedden, T., Park, D.C., Nisbett, R., Ji, L.-J., Jing, Q., Jiao, S., 2002. Cultural variation in verbal versus spatial neuropsychological function across the life span. Neuropsychology 16, 65.

Kensinger, E.A., Schacter, D.L., 1999. When true memories suppress false memories: effects of ageing. Cogn. Neuropsychol. 16, 399–415.

Kensinger, E.A., Schacter, D.L., 2008. Neural processes supporting young and older adults' emotional memories. J. Cogn. Neurosci. 20, 1161–1173.

Koutstaal, W., Schacter, D.L., 1997. Gist-based false recognition of pictures in older and younger adults. J. Mem. Lang. 37, 555–583.

Kumaran, D., Maguire, E.A., 2006. An unexpected sequence of events: mismatch detection in the human hippocampus. PLoS Biol. 4, e424.

Light, L.L., 1991. Memory and aging: four hypotheses in search of data. Annu. Rev. Psychol. 42, 333–376.

Loftus, E.F., Feldman, J., Dashiell, R., 1995. The reality of illusory memories. Memory distortion: How minds, brains, and societies reconstruct the past. Cambridge, MA: Harvard University Press, pp. 47–68.

McLaren, D.G., Ries, M.L., Xu, G., Johnson, S.C., 2012. A generalized form of context-dependent psychophysiological interactions (gPPI): a comparison to standard approaches. Neuroimage 61, 1277–1286.

Naveh-Benjamin, M., 2000. Adult age differences in memory performance: tests of an associative deficit hypothesis. J. Exp. Psychol. Learn. Mem. Cogn. 26, 1170.

Norman, K.A., 2010. How hippocampus and cortex contribute to recognition memory: revisiting the complementary learning systems model. Hippocampus 20, 1217–1227.

Norman, K.A., Schacter, D.L., 1997. False recognition in younger and older adults: exploring the characteristics of illusory memories. Mem. Cognit. 25, 838—848.

Park, D.C., Reuter-Lorenz, P., 2009. The adaptive brain: aging and neurocognitive scaffolding. Annu. Rev. Psychol. 60, 173.

Reuter-Lorenz, P.A., Park, D.C., 2014. How does it STAC up? Revisiting the scaffolding theory of aging and cognition. Neuropsychol. Rev. 24, 355—370.

Roediger, H.L., McDermott, K.B., 1995. Creating false memories: remembering words not presented in lists. J. Exp. Psychol. Learn. Mem. Cogn. 21, 803.

Rorden, C., Brett, M., 2000. Stereotaxic display of brain lesions. Behav. Neurol. 12, 191—200.

Schacter, D.L., 1999. The seven sins of memory: insights from psychology and cognitive neuroscience. Am. Psychol. 54, 182.

Schacter, D.L., 2008. Searching For Memory: The Brain, The Mind, And The Past. New York, NY: Basic Books.

Spencer, W.D., Raz, N., 1995. Differential effects of aging on memory for content and context: a meta-analysis. Psychol. Aging 10, 527.

Stark, S.M., Yassa, M.A., Stark, C.E., 2010. Individual differences in spatial pattern separation performance associated with healthy aging in humans. Learn Mem. 17, 284—288.

Tun, P.A., Wingfield, A., Rosen, M.J., Blanchard, L., 1998. Response latencies for false memories: gist-based processes in normal aging. Psychol. Aging 13, 230.

Wilson, I.A., Gallagher, M., Eichenbaum, H., Tanila, H., 2006. Neurocognitive aging: prior memories hinder new hippocampal encoding. Trends Neurosci. 29, 662—670.

Yassa, M.A., Mattfeld, A.T., Stark, S.M., Stark, C.E., 2011. Age-related memory deficits linked to circuit-specific disruptions in the hippocampus. Proc. Natl. Acad. Sci. U. S. A. 108, 8873—8878.

Yassa, M.A., Muftuler, L.T., Stark, C.E., 2010. Ultrahigh-resolution microstructural diffusion tensor imaging reveals perforant path degradation in aged humans in vivo. Proc. Natl. Acad. Sci. 107, 12687—12691.

Yassa, M.A., Stark, C.E., 2011. Pattern separation in the hippocampus. Trends Neurosci. 34, 515—525.

Yonelinas, A., 2002. The nature of recollection and familiarity: a review of 30 years of research. J. Mem. Lang. 46, 441—517.