Theneural basis of true memory and false memory for visual features:

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THE NEURAL BASIS OF TRUE MEMORY AND FALSE MEMORY FOR VISUAL FEATURES

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Episodic memory is a constructive process in which a system of sensory and control processes works to transport one's conscious mind through time–in essence, recreating a previous perceptual experience. For instance, sensory-specific activity that was associated with an original encoding experience is reinstated during retrieval–almost as if the sensory regions are processing the stimulus again, albeit this activation is smaller in spatial extent. This process of sensory-specific reinstatement occurs across all sensory modalities (e.g., Gottfried et al., 2004; Nyberg et al., 2001; Vaidya et al., 2002; Wheeler et al., 2000). That is, retrieval of a visually encoded stimulus (e.g., a picture of a dog) reinstates activity in the visual cortex, while retrieval of an aurally encoded stimulus (e.g., a barking dog) reinstates activity in the auditory cortex. In Chapter 1 and Chapter 2, I demonstrate the specificity of such sensory reinstatement during true memory for visual features and investigate the role of such sensory regions during the construction of false memory for visual features. In addition to sensory processes, our conscious experience of memory also relies on control regions. At the center of this memory control network sits a key memory structure, the hippocampus, as well as other important control regions such as the dorsolateral prefrontal cortex and the parietal cortex. Furthermore, the parahippocampal cortex appears to play a critical role in memory; however, the exact role of this region has been debated (Aminoff, Kverga, & Bar, 2013). In Chapter 3, I investigate the functional role of the parahippocampal cortex during true memory and false memory, and provide evidence that the parahippocampal cortex mediates general contextual processing.

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GENERAL INTRODUCTION

Episodic memory is a constructive process in which a system of control processes and sensory processes works to – in essence – transport one's conscious mind through time. At the center of the memory network sits a critical control region – the hippocampus, a region in the medial temporal lobe. In the absence of the hippocampus, long-term episodic retrieval can be severely impaired (for a review, see Squire & Wixted, 2011). Other important control regions include the dorsolateral prefrontal cortex, which mediates complex cognitive processes like source monitoring, working memory, and inhibitory control processes (for a review, see Gilboa, 2004), and the parietal cortex, which also supports conscious episodic retrieval (for a review, see Cabeza, 2008).

Of relevance to the present studies, regions of the sensory cortex also play an important role during episodic memory retrieval. For instance, sensory-specific activity that is associated with an original encoding experience is reinstated during retrieval, as if the sensory regions are processing the stimulus again (albeit this activation is smaller in spatial extent). This process of sensory-specific reinstatement occurs across all sensory modalities (Gottfried et al., 2004; Nyberg et al., 2001; Vaidya et al., 2002; Wheeler et al., 2000). For example, retrieval of a visually encoded stimulus reinstates activity in the visual cortex, while retrieval of an aurally encoded stimulus reinstates activity in the auditory cortex. Memory-related sensory reinstatement has also been demonstrated for specific visual features. That is, memory for colored items, but not grey items, reinstates activity in the color processing cortex (Slotnick, 2009a) and memory for shapes in the right visual field preferentially activate left visual cortical regions while shapes in the left visual field preferentially activate right visual cortical regions (Slotnick, 2009b).

Despite the elegance of our largely effective memory system, this constructive process is not immune from errors. Many studies have investigated the ways in which memory errors arise. One highly reliable demonstration of the imperfections of human memory is the Deese-Roediger-McDermott (DRM) paradigm, which capitalizes on the constructive, gist-based nature of memory. Roediger and McDermott (1995) implemented a behavioral paradigm in which participants heard lists of 12 words (e.g., table, sit, legs) that were each related to a single critical nonpresented lure (e.g., chair). At test, old words (e.g., table), critical lures (e.g., chair), and new words (e.g., pencil) were presented and participants were asked to determine whether each was old or new. Participants falsely recognized critical lures (e.g., chair) approximately 40% of the time. Highlighting the vividness that can be associated with such false memories, memories for the critical lure were associated high confidence ratings. Other false memory studies have demonstrated the manner in which the contents of our memory can be altered by misleading information. A large body of research has examined *the misinformation effect*– another robust effect in which post-event information (i.e., ideas, facts, and suggestions encountered after an event) alters memory for the original event (for a review, see Loftus, 2005). For instance, memories can be distorted by presenting a misleading narrative (Chan et al., 2009) or doctored photographs (Loftus, 1975). Furthermore, entirely new memories can be generated through suggestion. For instance, researchers have successfully implanted episodic memories of being previously lost in a mall or arrested in high school (Pickrell & Loftus, 1995). Together with a number of other behavioral experiments (e.g., Payne et al., 1997; Porter et al., 1999; Lampinen et al., 1998), these studies demonstrate that episodic memory can be imprecise/gist-based, altered by subsequent experiences, and completely fictional even despite feeling entirely real.

A number of neuroimaging studies have aimed to identify the neural underpinnings of episodic memory distortions. For a number of reasons (e.g., response limitations), many neuroimaging studies have investigated false memory via old-new recognition paradigms (e.g., Heun et al., 2000; Cabeza et al., 2001; Slotnick & Schacter, 2004; Garoff-Eaton et al., 2006, 2007; Hofer et al., 2007; Kim & Cabeza, 2007; Marchewka et al., 2008; Dennis et al., 2008;

Gionvanello et al., 2009; Dennis et al., 2012; Gutchess & Schacter, 2012; Iiadaka et al., 2012; Abe et al., 2013; Dennis et al., 2014). In these paradigms, items are presented in a list during a study phase. During the test phase, both old and new items are presented. In false memory studies, new items are of two types, related-new items and unrelated-new items, in which related-new items act as lures to increase false memory rates. Participants identify each item as “old” or “new” (in some studies, participants instead provide a “remember”, “know”, or “new” judgement for each item). False memory in the old-new paradigms is defined as endorsing an item as “old” when it was actually new. Other false memory studies have employed source memory paradigms during fMRI (e.g., Okado & Stark, 2003; Kensinger & Schacter, 2006; Stark et al., 2010). In such paradigms, items are presented in particular contexts during the study phase. Then, during the test phase, each old item is presented and participants identify the previous context of each item. In these studies, false memories are defined as remembering an item as previously within source/context A when it was actually in source/context B (this type of memory error is also called a source misattribution).

Such fMRI investigations employing old-new recognition paradigms and source memory paradigms suggest that true memory and false memory are largely associated with similar activity in control regions, including the dorsolateral prefrontal cortex, the parietal cortex, and medial temporal regions. Within old-new recognition paradigms, one prominent difference between true memory (“old”/old) and false memory (“old”/new) that has emerged is that true memory activity is greater than false memory activity within early visual processing regions (e.g., V1). It has been proposed that this activity in early sensory cortex results from rapid, nonconscious sensory reinstatement of the initial encoding experience for old items, as compared to new items. Thus, it appears that activity in the early sensory cortex reflects nonconscious processing, while higher-level conscious processing regions may ultimately give rise to the false memorial experience. Evidence from studies employing source memory paradigms further support this proposal.

Nonetheless, false memory can be quite detailed, and much remains unclear about how such false memories are constructed. In the present fMRI studies, we sought to better understand the nature of false memory construction by employing unique paradigms that elicited detailed false memories. Specifically, in all studies, false memory was defined as remembering that an item from encoding was previously associated with a particular visual feature (i.e., motion, shape, spatial location) when it was not previously associated with that particular visual feature. For instance, a false memory for the visual feature of motion was defined as remembering that an item was moving across the screen during encoding when it was actually stationary during encoding.

In Chapters 1 and 2, we investigated the role of visual cortical regions during the construction of true memory and false memory for specific visual features. One unique aspect of this paradigm is that it allowed us to assess whether false memory for a visual feature was associated with activity in that feature-specific sensory processing region. That is, does activation of the motion processing cortex give rise to false memory for motion (Chapter 1), and does activation of the shape processing cortex give rise to false memory for shape (Chapter 2)? Unlike previous investigations into false memory construction, the present studies permit us to directly assess whether erroneous activation of sensory cortex during retrieval is associated with feature-specific false memory. In Chapter 3, we assessed the role of the parahippocampal cortex during false memory. Of particular relevance, a debate exists as to whether the primary function of the parahippocampal cortex is to only process visual-spatial information or to more generally process contextual information (i.e., visual-spatial and non-spatial information). To anticipate the results, our findings indicate that the parahippocampal cortex is associated with general contextual processing.

PART 1

THE ROLE OF VISUAL CORTICAL REGIONS DURING MEMORY FOR VISUAL FEATURES

CHAPTER 1.0: MEMORY FOR MOTION

The cortical basis of true memory and false memory for motion

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Behavioral evidence indicates that false memory, like true memory, can be rich in sensory detail. By contrast, there is fMRI evidence that true memory for visual information produces greater activity in earlier visual regions than false memory, which suggests true memory is associated with greater sensory detail. However, false memory in previous fMRI paradigms may have lacked sufficient sensory detail to recruit earlier visual processing regions. To investigate this possibility in the present fMRI study, we employed a paradigm that produced feature-specific false memory with a high degree of visual detail. During the encoding phase, moving or stationary abstract shapes were presented to the left or right of fixation. During the retrieval phase, shapes from encoding were presented at fixation and participants classified each item as previously “moving” or “stationary” within each visual field. Consistent with previous fMRI findings, true memory but not false memory for motion activated motion processing region MT+, while both true memory and false memory activated later cortical processing regions. In addition, false memory but not true memory for motion activated language processing regions. The present findings indicate that true memory activates earlier visual regions to a greater degree than false memory, even under conditions of detailed retrieval. Thus, the dissociation between previous behavioral findings and fMRI findings do not appear to be task dependent. Future work will be needed to assess whether the same pattern of true memory and false memory activity is observed for different sensory modalities.

False memories can be rich in sensory detail under certain task conditions (Roediger & McDermott, 1995; Payne et al., 1997; Lampinen et al., 1998; Porter et al., 1999). For instance, Roediger and McDermott (1995) implemented a behavioral paradigm adapted from Deese (1959) in which participants heard lists of words (e.g., table, sit, legs, etc.) that were each related to a single critical nonpresented word (e.g., chair). The critical words were falsely recalled with high confidence, and "remember" judgment rates were not significantly different for true recognition of studied words and false recognition of critical nonpresented words.

By contrast, there is fMRI evidence that suggests true memories are associated with a greater degree of sensory detail as compared to false memories, as true memories have been associated with greater sensory cortical activity than false memories. In an fMRI study of memory for abstract shapes (Slotnick & Schacter, 2004), true memory activated earlier visual processing regions (BA 17, BA 18) to a greater degree than false memory, while both true memory and false memory equivalently activated later visual processing regions (BA 19, BA 37). In a more recent fMRI study (Stark et al., 2010), participants were presented with visual vignettes and, the following day, heard conflicting auditory misinformation (participants were under the impression that the auditory information was truthful). During the retrieval phase, participants were asked whether sentences accurately or inaccurately described previously presented vignettes. Consistent with previous findings (Slotnick & Schacter, 2004; see also, Garoff-Eaton et al., 2005), true memory produced greater activity in earlier visual processing regions (BA 17, BA 18) than false memory, while false memory for auditory misinformation produced activity in auditory/language processing regions (BA 22, BA 42). These fMRI results suggest true memory and false memory are distinct in that true memory produced greater activity than false memory in earlier visual processing regions, while true memory and false memory activated later processing regions to a similar degree.

The aim of the present study was to address the apparent discontinuity between previous behavioral results that suggest true memory and false memory can be associated with similar levels of subjective sensory detail, and the fMRI results that suggest true memory is associated with a greater degree of sensory detail than false memory. Specifically, previous fMRI paradigms may have produced false memory for modality-specific (e.g., visual) information without sufficient sensory detail to activate in earlier visual processing regions (see Slotnick, 2004). To investigate this possibility, in the present fMRI study we employed a paradigm to produce false memory for feature-specific (motion) information with a higher degree of visual detail than in previous fMRI studies (although these false memories may not be as detailed as true memories, which is addressed below). During the encoding phase, participants were presented with moving or stationary abstract shapes to the left or right of fixation (Figure 1, left). During the retrieval phase, shapes from encoding were presented at fixation and participants classified each item as previously “moving” or “stationary” within the “left” or “right” visual field (Figure 1, right). True memory corresponded to a “motion” response to a previously moving item, whereas false memory corresponded to a “motion” response to a previously stationary item.

Of importance, MT+ is the primary region involved in motion perception and memory for motion (Slotnick & Thakral, 2011), and thus can be assumed to mediate earlier visual processing in the present investigation. The pattern of true memory activity and false memory activity in MT+ and later cortical processing regions will be used to evaluate two hypotheses. If true memory and false memory for motion activate MT+ to a similar degree, this would support the hypothesis that false memories in previous fMRI studies did not have sufficient detail to activate earlier visual regions (i.e., the effects are task dependent). However, if true memory for motion still produces a greater magnitude of activity in MT+ than false memory for motion (with both true memory and false memory for motion producing activity in more anterior cortical regions), this would suggest false memory does not depend on earlier sensory cortical regions (i.e., there is a dissociation between behavioral and neural effects).

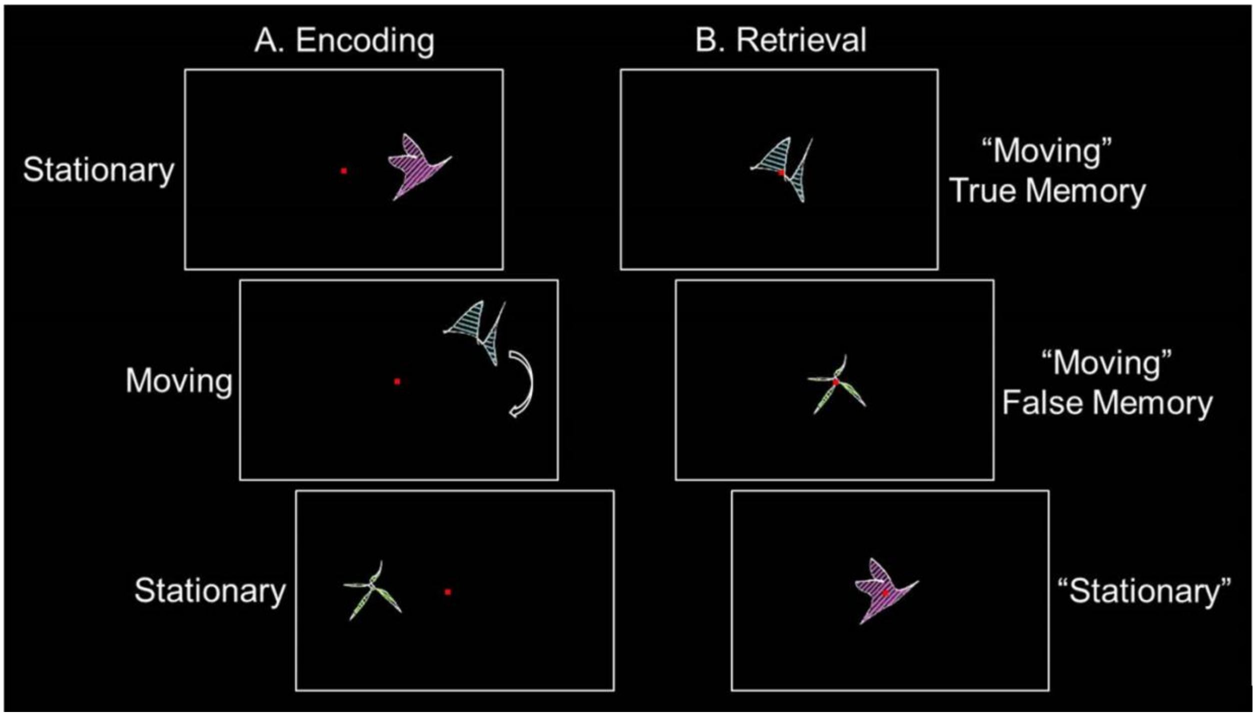

Figure 1. Stimulus paradigm and relevant event types. (A) During encoding, moving and stationary shapes were presented to the left or right of fixation. (B) During retrieval, shapes from encoding were presented at fixation and participants classified items as previously "moving" or "stationary" within the "left" or "right" visual field.

Methods

Participants

Twelve students at Boston College participated in the study (9 females, age range 19-28 years). Participants were right-handed, native English speakers, and had normal or corrected-to-normal vision. Participants were compensated $10 for the behavioral training session and $25/hour (approximately $100) for fMRI. The Boston College Institutional Review Board approved the behavioral protocol and the Massachusetts General Hospital Institutional Review Board approved the fMRI protocol. Informed and written consent was obtained before each session began.

Stimuli and procedure

Participants completed a behavioral training session, which included a one-quarter length memory run and two full-length memory runs, and six runs during fMRI. They were instructed to always maintain fixation and to remember whether each shape was moving or stationary and its spatial location (i.e., the left or right visual field). During the encoding phase of each run, 24 abstract shapes spanning 4° of visual angle were presented in the left or right visual field along an arc spanning ± 45° of polar angle from the horizontal meridian with the nearest edge 2° of visual angle from fixation. The shapes were designed to minimize verbal encoding strategies (for details on shape construction, see Slotnick & Schacter, 2004). Each shape was presented for 2.5 seconds with an inter-trial-interval of 3.0 seconds. Shape sets were repeated three times during encoding with each shape set randomized and presented sequentially. An equal number of shapes were stationary, at one of six equally spaced locations along the stimulation arc within each hemifield, or moving, smoothly traversing the entire stimulation arc in each hemifield with either upward or downward motion. In each run, all spatial locations and movement directions were presented equally often. Immediately before the retrieval phase, an instruction screen was presented for 8 seconds that reminded participants to maintain fixation and displayed the previously learned response mappings. During the retrieval phase of each run, the 24 shapes from encoding were presented in random order at fixation for 3.5 seconds with an inter-trial-interval of 7-10 seconds. Participants pressed response buttons with the fingers of their left hand to classify each shape as “previously in motion in the right visual field”, “previously in motion in the left visual field”, “previously stationary in the right visual field”, or “previously stationary in the left visual field”. Participants also made a subsequent “remember”-“know” response to characterize their subjective experience, but these responses were collapsed in the fMRI analysis to maximize power. During both encoding and retrieval, no more than three shapes of a given type were presented sequentially. Shapes were never repeated across runs. Sets of shapes (moving-right, moving-left, stationary-right, and stationary-left) were counterbalanced across participants using a Latin Square design.

Data acquisition and analysis

A Siemens 3 Tesla Trio Scanner (Erlangen, Germany) with a standard head coil was used to acquire data. To acquire functional images, an echo planar imaging sequence was used (TR = 2000 ms, TE = 20 ms, flip angle = 90°, field-of-view = 256 × 256 mm^2, acquisition matrix = 64 × 64, slices = 33, slice thickness = 4 mm, 4 mm isotropic resolution). To acquire anatomic images, a magnetized prepared rapid gradient echo sequence was used (TR = 30 ms, TE = 3.3 ms, flip angle = 40°, field-of-view = 256 × 256 mm^2, acquisition matrix = 256 × 256, slices = 128, slice thickness = 1.33 mm, 1.33 × 1 × 1 mm resolution). Analysis was conducted using Brain Voyager QX (Brain Innovation B.V., Maastrict, The Netherlands). Pre-processing included slice-time correction, motion correction, and temporal filtering by removal of linear trends and components at or below 2 cycles per run length (using a general linear model to remove low frequency Fourier basis sets). To maximize spatial resolution, spatial smoothing was not conducted. Functional and anatomic images were transformed into Talairach space.

A random-effect general linear model was conducted. To produce each hemodynamic response model, a canonical hemodynamic response function was convolved with the protocol of each event for each participant (i.e., a square wave defined by each event onset and the subsequent behavioral response). It was assumed that encoding trials had durations of 2.5 seconds and no-response trials had durations of 3.5 seconds. This produced the following event types: encoding type (moving or stationary) in the left or the right visual field, accurate memory for motion and spatial location, accurate memory for motion and inaccurate memory for spatial location, inaccurate memory for motion and spatial location, no response, and a constant. As we were only interested in memory for motion and it has been shown that MT+ is not modulated as a function of spatial location (Slotnick & Thakral, 2011), we collapsed over spatial location to maximize power.

Cortical regions associated with motion were identified by contrasting moving shapes at encoding > stationary shapes at encoding. Of relevance, motion processing region MT+ is known to be located within the ascending limb of the inferior temporal sulcus (Beauchamp et al., 2007; Dukelow et al., 2001; Huk et al., 2002; Smith et al., 2006; Watson et al., 1993). An individual voxel threshold of $p < 0.001$ was enforced for all contrasts, false discovery rate corrected for multiple comparisons to $p < 0.05$. Activations were localized on the group average anatomic volume (Talairach coordinates are provided in the tables), and were projected onto a representative inflated cortical surface for display purposes (for segmentation and reconstruction procedures, see Slotnick, 2005). Event-related activity was extracted in regions-of-interest (significant voxels within a 7 mm cube centered at each selected coordinate) from -2 to 12s after stimulus onset (baseline corrected from -2 to 0 s). Statistical analysis was based on the peak amplitude of activity from 6 to 8 s after stimulus onset, the expected maximum of the hemodynamic response, to avoid violation of independence.

Results

Behavioral accuracy for classifying moving items and stationary items was at an intermediate level (69.1 ± 3.0 % correct; “moving”/moving = 65.5 ± 4.4 %, “stationary”/moving = 34.5 ± 4.4 %, “moving”/stationary = 27.3 ± 4.1 %, “stationary”/stationary = 72.8 ± 4.1 %; chance = 50%, mean ± 1 se). The proportion of subsequent “remember” responses (i.e., $N_{\text{“remember”}}/N_{\text{“remember” + “know”}}$) was 79.8% for true memory (“moving”/moving) and 62.9% for false memory (“moving”/stationary). This indicates that the majority of true memories and false memories were detailed, although the “remember” rate was significantly higher for true memories (t (11) = 2.35, $p < 0.05$).

Activity associated with perception/encoding of moving shapes (moving > stationary) occurred in motion processing region MT+ bilaterally within the ascending limb of the inferior temporal sulcus (Figure 2; in yellow). Activity associated with true memory for motion (identified by contrasting “moving”/moving items > “stationary”/moving items; i.e., hit > miss; in red) occurred in MT+ bilaterally (Figure 2; overlap with motion perception/encoding activity in orange). In addition, true memory for motion produced activity in many other cortical regions, including more anterior temporal regions (Figure 2; in red). There was no significant activity within MT+ associated with false memory for motion (identified by contrasting “moving”/stationary items > “stationary”/stationary items; in green), even at a reduced threshold ($p < 0.01$, uncorrected). Like true memory, false memory for motion activated more anterior temporal regions (Figure 2; in green). Furthermore, false memory but not true memory for motion produced activity in language processing cortex (BA 44/Broca’s area; for a complete list of activations, see Table 1). The magnitude of activity (% signal change) associated with true memory and false memory was extracted from MT+ and BA 44 to better characterize the response profiles within these regions. Within MT+ (Figure 2, bottom right), the magnitude of true memory activity (“moving”/moving – “stationary”/moving) was significantly positive ($t(11) = 2.22$, $p < 0.05$), but the magnitude of false memory activity (“moving”/stationary – “stationary”/stationary) was not significantly positive ($t(11) < 1$; the “moving”/moving magnitude was also significantly positive, $t(11) = 3.51$, $p < 0.01$, and the “moving”/stationary magnitude was not significantly positive, $t(11) = 1.71$, $p = 0.057$). Within BA 44 (Figure 2, bottom left), the magnitude of true memory activity (“moving”/moving – “stationary”/moving) was not significantly positive ($t(11) = 1.00$, $p = 0.17$), but the magnitude of false memory activity (“moving”/stationary – “stationary”/stationary) was significantly positive ($t(11) = 2.42$, $p < 0.05$; the “moving”/moving magnitude was also not significantly positive, $t(11) = 1.49$, $p = 0.082$, and the “moving”/stationary magnitude was significantly positive, $t(11) = 3.63$, $p < 0.01$).

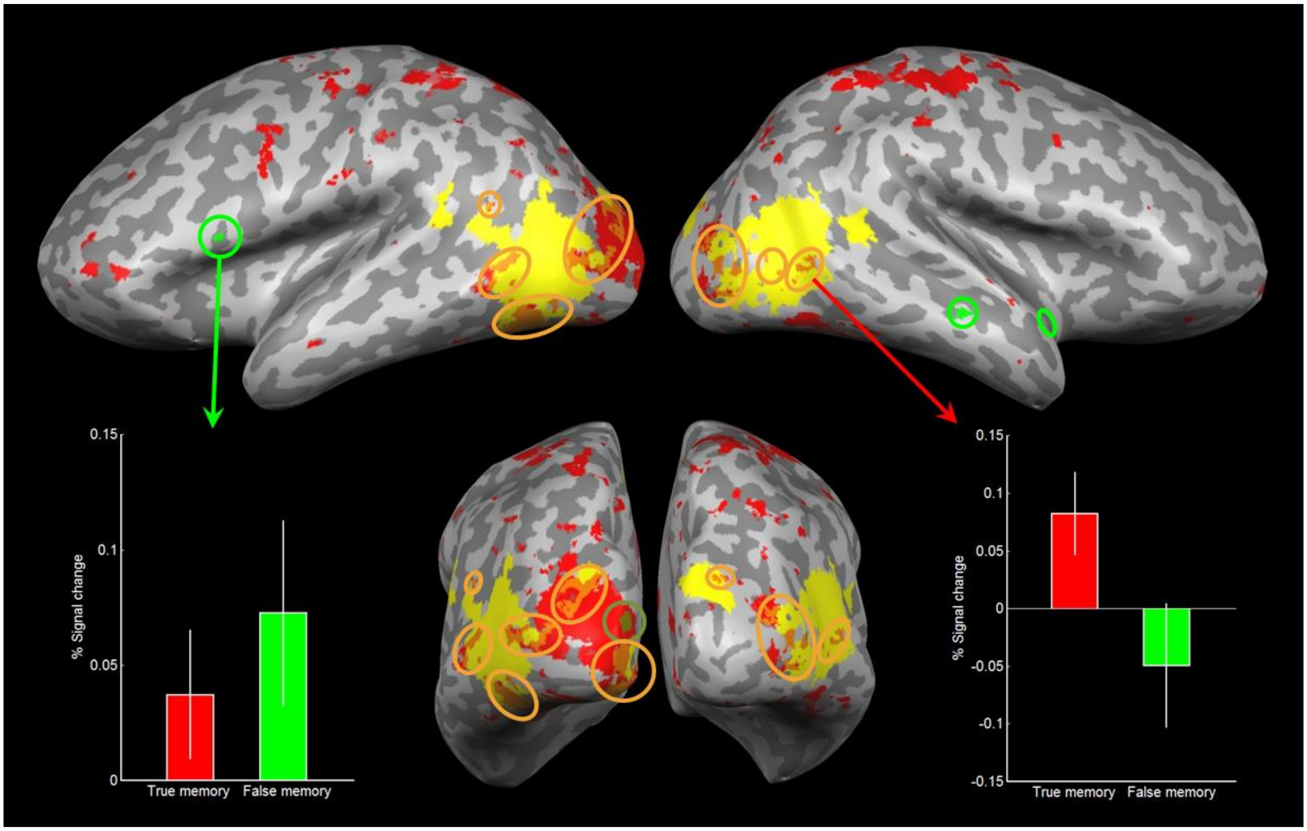

Figure 2. Activity associated with true memory for motion and false memory for motion. Gyri and sulci are shown in light and dark gray, respectively (lateral views are shown at the top and a posterior view is shown at the bottom). Activity associated with motion perception/encoding is shown in yellow. Activity associated with true memory for motion is shown in red (overlap with motion perception/encoding is shown in orange within orange ovals). Activity associated with false memory for motion is shown in green (within green ovals; overlap with motion perception/encoding is shown in olive within olive oval). True memory and false memory activation magnitudes (% signal change) were extracted from BA44 (bottom left) and MT+ (bottom right; mean ± 1 se).

We next evaluated whether the magnitude of activity in motion processing cortex associated with true memory was significantly greater than that associated with false memory. Activity associated with true memory versus false memory for motion (identified by contrasting “moving”/moving items > “moving”/stationary items) occurred in motion processing cortex (Figure 3; overlap with motion perception/encoding activity in orange). Activity associated with false memory versus true memory for motion (the reverse contrast) did not activate motion processing cortex (Figure 3, in green), even at a reduced threshold ($p < 0.01$, uncorrected).

False memory versus true memory activated language processing cortex (BA 22/Wernicke's area; for a complete list of activations, see Table 2).

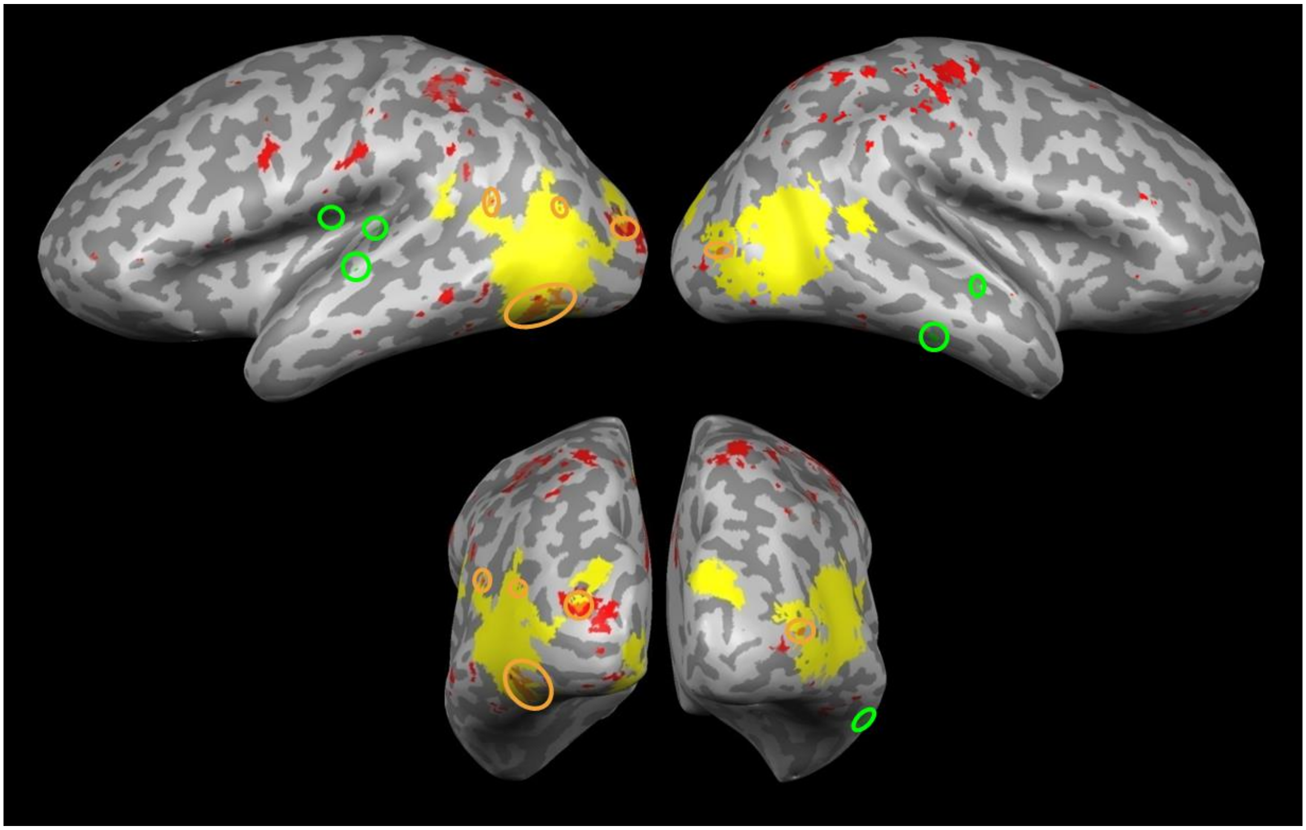

Figure 3. Activity associated with true memory versus false memory for motion. Activity associated with motion perception/encoding is shown in yellow. Activity associated with true memory greater than false memory for motion is shown in red (overlap with motion perception/encoding is shown in orange, within orange ovals). Activity associated with false memory greater than true memory for motion is shown in green (within green ovals).

The preceding behavioral analysis showed that the "remember" rate was significantly higher for true memory than false memory. As such, it could be argued that our differential fMRI findings in MT+ reflected more detailed processing during true memory. In an effort to equate the level of detail during true memory and false memory, we conducted a post-hoc individual participant behavioral analysis. We found that the differential "remember" response rates for true memory and false memory were driven by four participants (i.e., the differential response rates had a bimodal distribution; four participants had values > 0.29 and the remaining participants had values < 0.12). After the four participants with the highest differential "remember" response rates were eliminated from the behavioral analysis, the "remember" response rates for true memory (77.2%) and false memory (74.5%) did not significantly differ (*t*(7) < 1; location accuracy did not significantly differ for these participants either, *t*(7) = 1.78, *p* = 0.12). It is notable that this false memory "remember" response rate is similar to that reported during the Deese-Roediger-McDermott paradigm (Roediger & McDermott, 1995). The fMRI analysis was conducted using the participants with matched true memory and false memory "remember" rates, and we observed the identical pattern of results described above.

Discussion

In the present study, true memory for motion produced greater activity in motion processing region MT+ than false memory for motion, while both true memory and false memory for motion produced activity in more anterior temporal regions. The identical pattern of activity was observed when subjective detail was equated. These results support previous fMRI findings (Slotnick & Schacter, 2004; Stark et al., 2010) that true memory produces greater activity in earlier sensory processing regions than false memory, and that true memory and false memory produce similar patterns of activity in later sensory processing regions.

These findings support the hypothesis that there is a dissociation between behavioral results that indicate true memory and false memory can have a similar degree of sensory detail (Roediger & McDermott, 1995; Payne et al., 1997; Lampinen et al., 1998; Porter et al., 1999; but see, Henkel et al., 2000), and fMRI results that indicate true memory is associated with a higher degree of sensory detail than false memory (Slotnick & Schacter, 2004; Stark et al., 2010). The current paradigm was designed to produce false memory for feature-specific (motion) information, rather than modality-specific information as employed in previous fMRI studies (Slotnick & Schacter, 2004; Stark et al., 2010), such that false memory for motion might have produced activity in MT+, yet no such activity was observed. Considering the consistent pattern of true memory and false memory activity across the present and previous fMRI studies, the neural basis of true memory and false memory for visual information does not appear to be task dependent. The discrepancy between the behavioral findings, which suggest false memory can be highly detailed, and fMRI findings, which suggest false memory is not highly detailed, needs to be reconciled. It appears that the detailed subjective experience associated with behavioral false memory does not reflect feature-specific sensory processing, which would have been manifested in the present study by activation of MT+, but rather reflects high confidence based on activity in later processing regions. Of note, Chua et al. (2004) showed that the left inferior frontal gyrus was engaged during memory judgments of high confidence, regardless of memory accuracy (see also, Kao et al., 2005). Based on this evidence, false memory for motion in the current paradigm may have been mediated, in part, by activity in the left inferior frontal gyrus (BA 44; Table 1). However, we acknowledge the possibility that the null effects (i.e., no true memory activity in BA 44, and no false memory activity in MT) could possibly reach significance if power was increased. Although, the present sample size does fall within the standard range.

More broadly, the present results fit within a constructive memory framework (see Schacter et al., 1998). This framework has been supported by evidence from the visual, auditory/language, olfactory, and motor modalities (e.g., Nyberg et al., 2001, Vaidya et al., 2002; Wheeler & Buckner, 2004; Gottfried et al., 2004; Garoff-Eaton et al., 2005; for a review, see Slotnick, 2004). To illustrate, true memory for visual and auditory information (i.e., pictures and sounds) produced activity in visual and auditory processing cortex (Wheeler et al., 2000), and false memory for visual information (i.e., abstract shapes) produced activity in language processing cortex (Garoff-Eaton et al., 2005). More recent studies have provided feature-specific evidence that is even more compelling support for the constructive memory framework during true memories. For instance, memory for color has been shown to reactivate color processing region V8 (Slotnick, 2009a), memory for spatial location has been shown to reactivate contralateral/retinotopic extrastriate cortex (Slotnick, 2009b), and memory for motion has been shown to reactivate motion processing region MT+ (Slotnick & Thakral, 2011). In the present study, true memory for motion also activated MT+, whereas false memory for motion did not activate this region. However, false memory for motion did rely on more anterior cortical regions involved in processing non-detailed visual information, including language processing regions that represent the verbal label “motion” that was sometimes incorrectly attributed to stationary shapes. In support of this possibility, Garoff-Eaton et al. (2005) showed rates of false memory positively correlated with recruitment of language processing regions (i.e., BA 22, 38, and 44) during retrieval, which suggests that the false memories in the present paradigm may be mediated by verbal labeling strategies.

The present feature-specific fMRI results support and extend previous modality-specific fMRI findings (Slotnick & Schacter, 2004; Stark et al., 2010) that have indicated true memory but not false memory is associated with activity in earlier sensory regions while both true memory and false memory are associated with activity in later sensory regions. Considered together, these fMRI results provide support for the same pattern of true memory and false memory activity in both domain-specific and feature-specific paradigms. Future work will be needed to assess whether this pattern of activity is observed for different sensory modalities.

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Tables

Table 1. True memory and false memory activations.

Region	BA	x	y	z
True Memory				
Anterior Frontal Cortex	10	16	55	-3
Anterior Frontal Cortex	10	35	55	12
Anterior Frontal Cortex	10	-40	42	2
Medial Frontal Cortex	12	-4	45	-9
Anterior Frontal Cortex	10	-32	43	10
Middle Frontal Gyrus	46	-39	40	26
Anterior Frontal Cortex	10	-38	46	-3
Middle Frontal Gyrus	9/46	-30	30	20
Orbital Frontal Cortex	11	26	32	-5
Anterior Cingulate	24	5	31	7
Orbital Frontal Cortex	11	-26	28	-13
Inferior Frontal Sulcus	9	41	24	26
Inferior Frontal Sulcus	9	-37	18	22
Superior Frontal Gyrus	6	-13	16	57
Anterior Cingulate	24	-11	16	30
Medial Frontal Cortex	6	-4	13	48
Medial Frontal Cortex	6	-9	6	48
Precentral Gyrus	6	52	-2	33
Middle Frontal Gyrus	6	-33	1	41
Precentral Sulcus	6	-52	2	32
Superior Frontal Gyrus	6	-3	-3	58
Precentral Gyrus	6	36	-1	33
Central Sulcus	3/4	27	-14	49
Precentral Sulcus	4	42	-4	46
Precentral Sulcus	6	-19	-13	52
Superior Temporal Gyrus	22	56	-4	-6
Supramarginal Gyrus	40	-58	-17	25
Intraparietal Sulcus	40	-49	-20	37
Intraparietal Sulcus	40	-38	-26	44
Superior Parietal Lobule	7	30	-44	52
Supramarginal Gyrus	40	44	-29	35
Superior Parietal Lobule	7	-34	-36	48
Middle Temporal Gyrus	21	-55	-9	-15
Right Amygdala	-	30	-13	-9
Left Amygdala	-	-31	-13	-8
Superior Temporal Gyrus	22/42	-61	-29	18
Superior Temporal Gyrus	22	-59	-32	12
Posterior Cingulate	31	6	-53	28
Fusiform Gyrus	19/37	36	-61	-12
Striate and Extrastriate Cortex	17/18/19/37	-17	-94	6
Fusiform Gyrus	19/37	-28	-69	-13
Extrastriate Cortex	19	43	-61	4
Superior Parietal Lobule	7	-20	-61	52
Posterior Intraparietal Sulcus	19/39	20	-63	39
Precuneus	7	-5	-74	41
Extrastriate Cortex	18/19	28	-84	7

False Memory				
Inferior Frontal Gyrus	44	-40	10	12
Superior Temporal Sulcus	21	51	-20	-9
Extrastriate Cortex	18	-22	-89	18
Extrastriate Cortex	18	-13	-92	12

BA refers to Brodmann area and Talairach coordinate (x, y, z) refers to the center of activation.

Table 2. True memory > false memory and false memory > true memory activations.

Region	**BA**	**x**	**y**	**z**
True Memory > False Memory				
Anterior Frontal Cortex	10	-34	47	3
Middle Frontal Gyrus	46	-28	37	26
Middle Frontal Gyrus	46	29	37	24
Orbital Frontal Cortex	11	23	35	-5
Inferior Frontal Sulcus	9/46	39	27	21
Medial Frontal Cortex	32	10	26	34
Superior Frontal Sulcus	6	17	10	45
Middle Frontal Gyrus	6	-25	5	45
Precentral Sulcus	6	-39	-2	47
Precentral Sulcus	6	-51	2	32
Postcentral Sulcus	2	47	-20	34
Postcentral Gyrus	1	54	-14	36
Postcentral Sulcus	2	-53	-19	27
Postcentral Sulcus	2	31	-23	47
Postcentral Sulcus	2	-36	-28	36
Intraparietal Sulcus	7/40	-34	-46	46
Supramarginal Gyrus	40	53	-44	35
Intraparietal Sulcus	40	35	-51	35
Superior Temporal Sulcus	21	55	-5	-10
Inferior Temporal Sulcus	37	-58	-35	-12
Inferior Temporal Sulcus	21/37	-54	-43	-4
Superior Parietal Lobule	7	19	-59	54
Fusiform Gyrus	19/37	-46	-64	-12
Extrastriate Cortex	18	-24	-83	13
Extrastriate Cortex	19	39	-83	3
Extrastriate Cortex	19	-22	-83	-9
Extrastriate Cortex	19	31	-85	2
Extrastriate Cortex	19	-28	-88	7
Extrastriate Cortex	18	-10	-89	-10
False Memory > True Memory				
Central Sulcus	3	49	-5	18
Lateral Sulcus	40	-39	-16	18
Superior Temporal Sulcus	22	-58	-17	-1
Superior Temporal Sulcus	21/22	50	-17	-6
Inferior Temporal Sulcus	37	49	-26	-14
Lateral Sulcus	41	-40	-29	12
Extrastriate Cortex	18	10	-65	5

BA refers to Brodmann area and Talairach coordinate (x, y, z) refers to the center of activation.

CHAPTER 2.1: TRUE MEMORY FOR SHAPE

Memory for shape reactivates the lateral occipital complex

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Memory is thought to be a constructive process in which the cortical regions associated with processing event features are reactivated during retrieval. Although there is evidence for non-detailed cortical reactivation during retrieval (e.g., memory for visual or auditory information reactivates the visual or auditory processing regions, respectively), there is limited evidence that memory can reactivate cortical regions associated with processing detailed, feature-specific information. Such evidence is critical to our understanding of the mechanisms of episodic retrieval. The present functional magnetic resonance imaging (fMRI) study assessed whether the lateral occipital complex (LOC), a region that preferentially processes shape, is associated with retrieval of shape information. During encoding, participants were presented with colored abstract shapes that were either intact or scrambled. During retrieval, colored disks were presented and participants indicated whether the corresponding shape was previously "intact" or "scrambled". To assess whether conscious retrieval of intact shapes reactivated LOC, we conducted a conjunction of shape perception/encoding and accurate versus inaccurate retrieval of intact shapes, which produced many activations in LOC. To determine whether activity in LOC was specific to intact shapes, we conducted a conjunction of shape perception/encoding and intact versus scrambled shapes, which also produced many activations in LOC. Furthermore, memory for intact shapes in each hemifield produced contralateral activity in LOC (e.g., memory for left visual field intact shapes activated right LOC), which reflects the specific reinstatement of perception/encoding activity. The present results extend previous feature-specific memory reactivation evidence and support the view that memory is a constructive process.

Memory is thought to be a constructive process in which cortical regions associated with processing event features during perception/encoding are reactivated during retrieval (for a review, see Schacter et al., 1998). That is, the construction of a memory, which is comprised of multiple features, can be described as linking the features that are processed in different cortical regions. For example, retrieval of visual information (i.e., pictures) and auditory information (i.e., sounds) reactivates visual and auditory processing regions (Wheeler et al., 2000; see also, Nyberg et al., 2000; Stark et al., 2004; Vaidya et al., 2002), retrieval of actions reactivates motor processing regions (Nilsson et al., 2000; Nyberg et al., 2001), and retrieval of odors reactivates olfactory processing regions (Gottfried et al., 2004). These findings provide support for the constructive memory framework in which sensory activity that is associated with perception/encoding is reinstated during retrieval.

There is also evidence that sensory reactivation occurs during more detailed, feature-specific memories. Specifically, memory for color reactivates color processing region V8 (Simmons et al., 2007; Slotnick, 2009a), memory for motion reactivates motion processing region MT+ (Karanian & Slotnick, 2014; Slotnick & Thakral, 2011; Ueno et al., 2009), and memory for spatial location reactivates contralateral extrastriate cortex (i.e., shapes previously presented in the right visual field reactivate left extrastriate regions, and vice versa; Slotnick, 2009b). These feature-specific results provide compelling evidence that visual details from perception/encoding are reactivated during retrieval. However, to our knowledge, no studies have investigated whether memory for shape reactivates the lateral occipital complex (LOC), a region that preferentially processes shape.

In the present study, we investigated whether memory for shape reactivates LOC. LOC is comprised of multiple sub-regions including a lateral occipital region adjacent to MT/ V5, which is referred to as LO, and a ventral region that lies within the posterior fusiform gyrus, which is referred to as pFs (Grill-Spector et al., 1998; 2000; 2001; Kourtzi & Kanwisher, 2000; 2001; Larsson & Heeger, 2006; Liu et al., 2004; Malach et al., 1995; 2002). In terms of function, LOC generally responds to shapes and objects to a greater degree than textures, patterns, and random visual noise (Malach et al., 1995). LOC is also more responsive during perception of intact images than scrambled images under numerous stimulus manipulations (i.e., lines, shading, texture, and depth cues; Kourtzi & Kanwisher, 2000), and neurons within LOC decrease in firing rate as images become more scrambled (Grill-Spector et al., 1998). It has also been suggested that LOC processes higher-level shape information, as opposed to lower-level feature information (Kourtzi & Kanwisher, 2001), and its activity is correlated with accurate object perception (Grill-Spector et al., 2000). Reiterating the role of LOC in higher-level representation of shape, this region is also active during mental imagery of geometric properties (Newman et al., 2005; see also, Deshpande et al., 2010).

During the encoding phase of the current study, participants viewed a series of intact shapes and scrambled shapes that were each presented in a unique color (Figure 1, left). During the retrieval phase, colored disks were presented in the center of the screen and participants were asked to classify the corresponding shape as previously “intact” or “scrambled” in the “left” or “right” visual field (Figure 1, right). To localize LOC, we contrasted perception/encoding of intact shapes and scrambled shapes (i.e., encoding-intact shapes > encoding-scrambled shapes). Activity associated with memory for intact shapes was isolated by contrasting accurate retrieval of intact shapes and inaccurate retrieval of intact shapes (i.e., intact-hits > intact-misses) in addition to contrasting accurate retrieval of intact shapes and accurate retrieval of scrambled shapes (i.e., intact-hits > scrambled-hits). Based on the constructive memory framework, we hypothesized that memory for intact shapes would activate LOC.

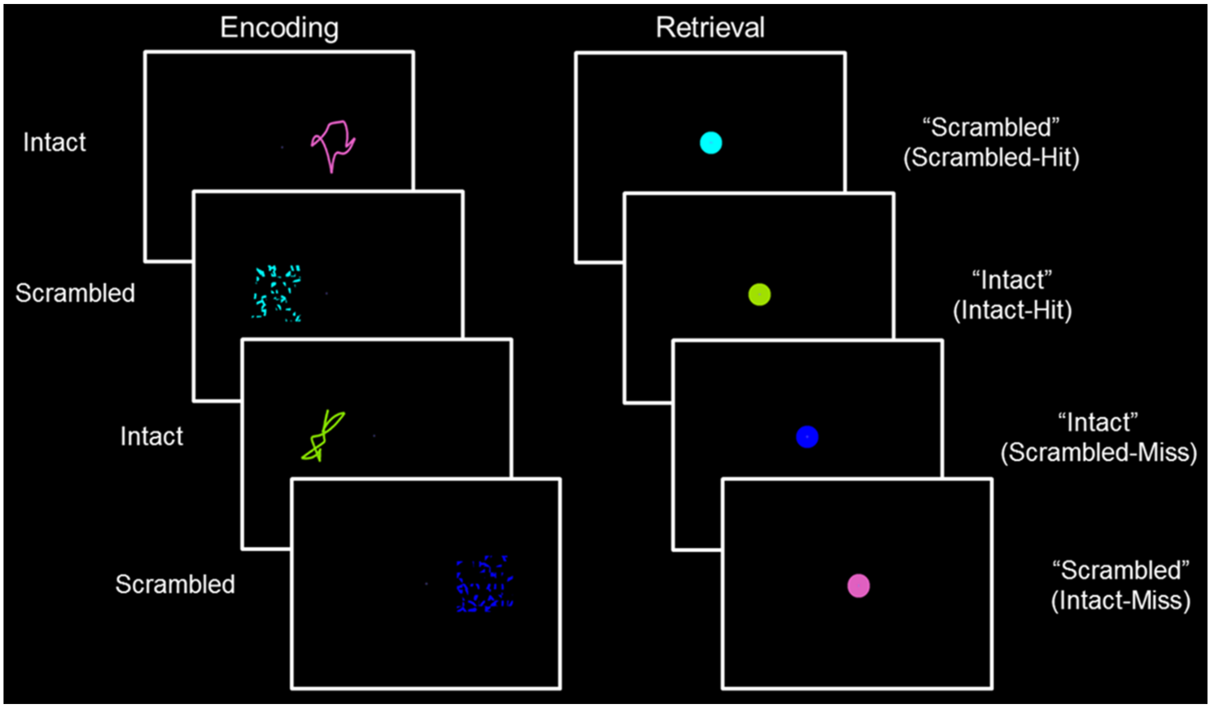

Figure 1. Stimulus paradigm and responses. At encoding, intact or scrambled shapes were presented to the left or right of fixation. At retrieval, colored disks were presented at fixation and participants classified the corresponding item as previously "intact" or "scrambled" within the "left" or "right" visual field. Example responses and event types are shown to right.

Methods

Participants

Fourteen Boston College undergraduate students participated in the study (6 females, age range 19-22 years). Participants were right-handed, native English speakers, had normal or corrected-to-normal vision, and were compensated $10 for the behavioral training session and $25/hour (approximately $100) for the fMRI session. Informed and written consent was obtained before each session began. The Boston College Institutional Review Board approved the protocol.

Stimuli and procedure

Participants completed a behavioral training session, which included a one-fourth length memory run and one or two full-length memory runs, and nine memory runs during fMRI. During the encoding phase of each run, 16 uniquely colored intact or scrambled shapes spanning 4.6° of visual angle were presented in the left or right visual field with the nearest edge 2.5° of visual angle from fixation (Figure 1, left). Intact shapes were designed to minimize verbal encoding strategies (for details on shape construction, see Slotnick & Schacter, 2004). Each scrambled shape was created by superimposing a 10 x 10 grid over the bounding box of an intact shape and then reassigning each pixel to a random location within the grid. Each shape was presented for 2.5 seconds with an inter-trial-interval of 3.0 seconds. Each shape set was randomized and presented sequentially five times. Shapes and colors were never repeated across runs. Shape sets (intact-left, intact-right, scrambled-left, and scrambled-right) were counterbalanced across participants using a Latin Square design. Participants were instructed to always maintain fixation and to remember each shape and its spatial location.

Immediately before the retrieval phase of each run, an instruction screen was presented for 8 seconds that reminded participants to maintain fixation and displayed the previously learned response mappings. During the retrieval phase of each run, 16 colored disks corresponding to the previously studied shapes were presented in random order at fixation (Figure 1, right). Each disk spanned 1.8° of visual angle and was presented for 3.5 seconds with an inter-trial-interval of 7-10 seconds. Participants pressed response buttons with the fingers of their left hand to classify the shape corresponding to the colored disk as previously “intact” or “scrambled” in the “left” or “right” visual field. Participants also made a subsequent “remember”-“know” response to characterize their subjective experience, but these responses were collapsed to maximize power. During both encoding and retrieval, no more than three items of a given type were presented sequentially.

Data Acquisition and Analysis

Data were acquired with a Siemens 3 T Trio Scanner (Erlangen, Germany). An echo planar imaging sequence was used to acquire functional images (TR = 2000 ms, TE = 20 ms, flip angle = 90°, field-of-view = 256 mm × 256 mm, acquisition matrix = 64 × 64, slices = 33, slice thickness = 4 mm; 4 mm isotropic resolution). A magnetized prepared rapid gradient echo sequence was used to acquire anatomic images (TR = 30 ms, TE = 3.3 ms, flip angle = 40°, field-of-view = 256 mm × 256 mm, acquisition matrix = 256 × 256, slices = 128, slice thickness = 1.33 mm; 1.33 × 1 × 1 mm resolution). Analysis was conducted using Brain Voyager QX (Brain Innovation B.V., Maastrict, The Netherlands). Pre-processing included slice-time correction, motion correction, and temporal filtering by removal of linear trends and components at or below 2 cycles per run length (using a general linear model to remove low frequency Fourier basis sets). To maximize spatial resolution, spatial smoothing was not conducted. Anatomic and functional images were transformed into Talairach space.

A random-effect general linear model was conducted. For each participant, a canonical hemodynamic response function was convolved with the protocol of each event to produce each hemodynamic response model (i.e., a square wave defined by each event onset and the subsequent behavioral response). It was assumed that encoding trials had durations of 2.5 seconds and no-response trials at retrieval had durations of 3.5 seconds. The following event types were entered into the general linear model for the primary analysis: accurate subsequent memory for shape and spatial location, accurate subsequent memory for shape and inaccurate spatial memory for spatial location, inaccurate subsequent memory for shape and spatial location, accurate memory for shape and spatial location, accurate memory for shape and inaccurate memory for spatial location, inaccurate memory for shape and spatial location, no response, and a constant. As we were primarily interested in memory for shape, unless otherwise specified, we collapsed over spatial location to maximize power.

LOC was localized by contrasting perception/encoding of intact shapes and perception/encoding of scrambled shapes (i.e., encoding-intact > encoding-scrambled; Grill-Spector et al., 1998; 2000; 2001; Hemond et al., 2007; Kourtzi & Kanwisher, 2000; 2001; Larsson & Heeger, 2006; Malach et al., 1995; 2002; McKyton & Zohary, 2007; Niemeier et al., 2005; Sayres & Grill-Spector, 2008). An individual voxel threshold of $p < 0.005$ was enforced for all contrasts, which corresponds to a joint probability of $p < 0.001$ for all conjunctions (false discovery rate corrected to $p < 0.05$). Activations were localized on the group average anatomic volume and projected onto an inflated cortical surface for display purposes (for segmentation and reconstruction procedures, see Slotnick, 2005). Coordinates refer to the center of each activation.

Results

Shape Encoding

The contrast of perception/encoding of intact shapes and perception/encoding of scrambled shapes (encoding-intact > encoding-scrambled) produced bilateral activity in LOC. The LOC Talairach coordinates for left LO (x = -46, y = -68, z = -7), right LO (x = 40, y = -67, z = -6), left pFs (x = -44, y = -52, z = -15), and right pFs (x = -37, y = -52, z = -17) are consistent with previous findings (Grill-Spector et al., 1998; 2000; Malach et al., 1995; Niemeier et al., 2005).

Intact Shape Retrieval

To test our hypothesis that retrieval of intact shapes reactivates LOC, we conducted a conjunction of perception/encoding of intact versus scrambled shapes (encoding-intact > encoding-scrambled) and accurate versus inaccurate retrieval of intact shapes (intact-hits > intact-misses; this contrast isolates conscious memory of intact shapes). This conjunction produced many activations in LOC, including LO and pFs (Figure 2; Table 1, top).

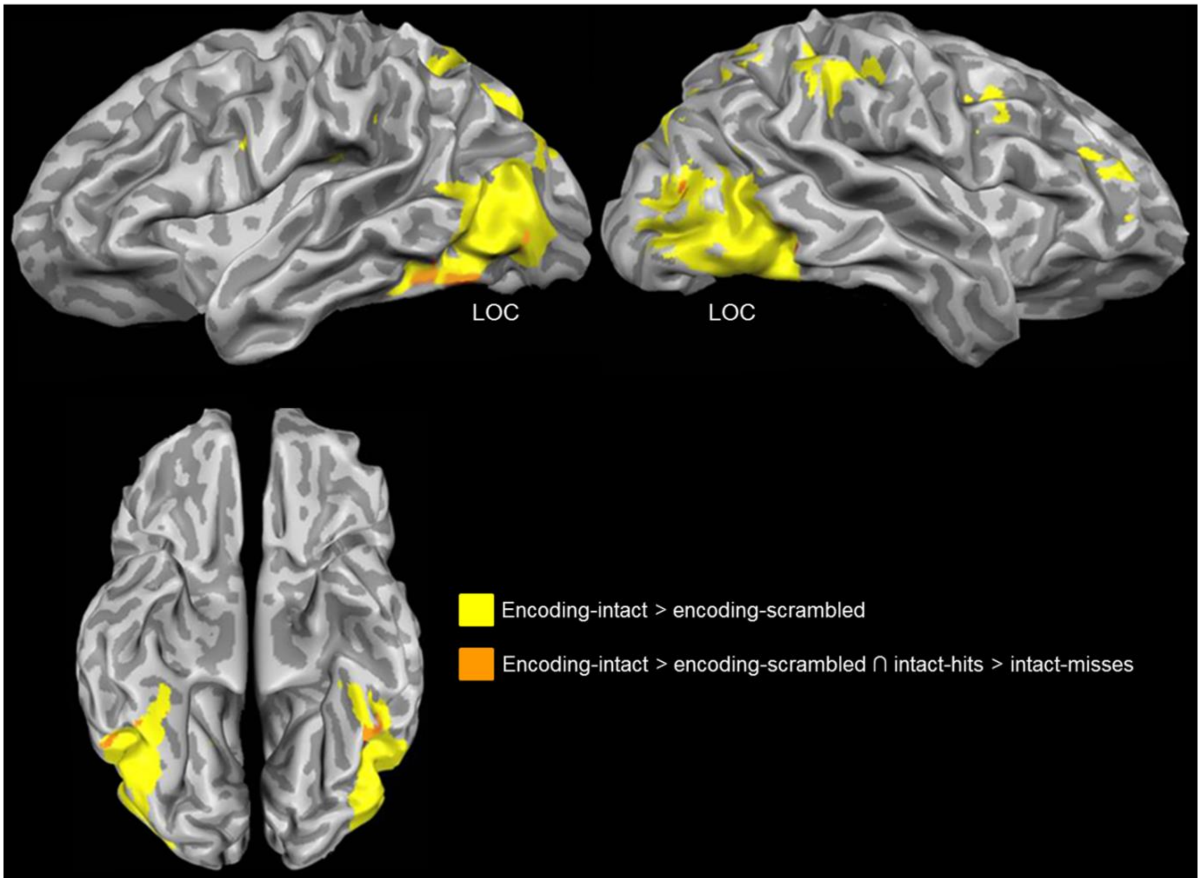

Figure 2. Conscious memory for intact shapes activates LOC. LOC activity associated with shape perception/encoding (encoding-intact > encoding-scrambled), shown in yellow, and the conjunction of perception/encoding and accurate intact shape retrieval (intact-hits > intact-misses), shown in orange. (key to the bottom right; gyri and sulci are shown in light and dark gray, respectively; top, lateral views; bottom, inferior view).

To assess whether reactivation of LOC was preferentially associated with memory for intact shapes, we conducted a conjunction of perception/encoding of intact versus scrambled shapes (encoding-intact > encoding-scrambled) and accurate retrieval of intact versus scrambled shapes (intact-hits > scrambled-hits). This conjunction also produced many activations in LOC (Figure 3; Table 1, middle).

We also conducted the triple conjunction of perception/encoding of intact versus scrambled shapes (encoding-intact > encoding-scrambled), accurate versus inaccurate retrieval of intact shapes (intact-hits > intact-misses), and accurate retrieval of intact versus scrambled shapes (intact-hits > scrambled-hits). This conjunction, which identified LOC activity that was associated with conscious memory for intact shape and specific to intact shapes, also produced activity in LOC (Table 1, bottom).

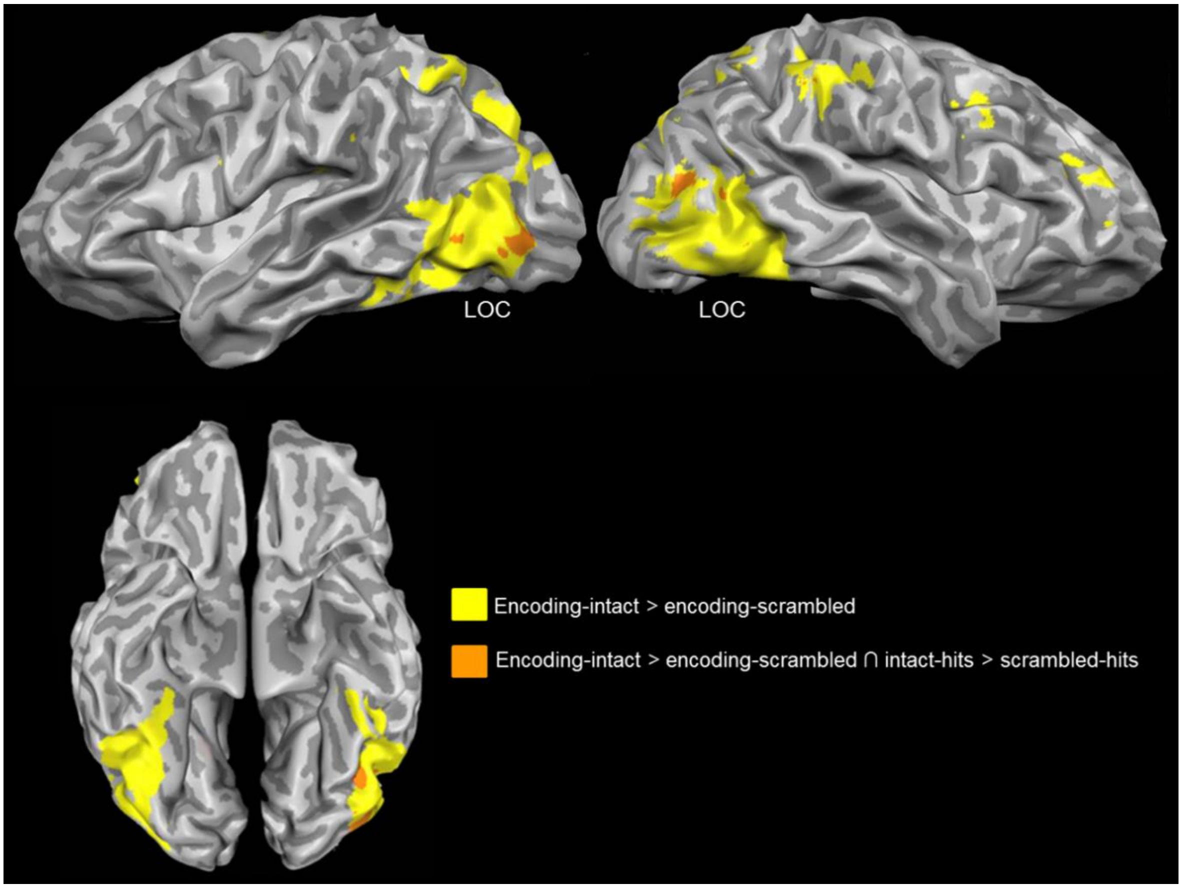

Figure 3. Memory for intact shapes preferentially activates LOC. LOC activity associated with shape perception/encoding (encoding-intact > encoding-scrambled), shown in yellow, and the conjunction of perception/encoding and intact shape retrieval (intact-hits > scrambled-hits), shown in orange (key to the bottom right).

Retinotopy in LOC

Previous perception studies have reported that LOC is retinotopic (Hemond et al., 2007; McKyton & Zohary, 2007; Niemeier et al., 2004; Sayres & Grill-Spector, 2008), where shapes in the left and right visual field preferentially activated right and left LOC. To determine whether our memory reactivation effects were also retinotopic, we conducted the previous triple conjunction for items in the left visual field and the right visual field. For left visual field stimuli, we conducted the conjunction of perception/encoding of intact versus scrambled shapes (encoding-left-intact > encoding-left-scrambled), accurate versus inaccurate retrieval of intact shapes (intact-left-hit >

intact-left-misses), and accurate retrieval of intact versus scrambled shapes (intact-left-hits > scrambled-left-hits). This conjunction for left visual field stimuli produced a single activation in right LO (Talairach coordinates x = 44, y = -74, z = 12; Figure 4A). The analogous conjunction for right visual field stimuli produced a single activation in left LO (x = -37, y = -65, z = -3; Figure 4B). These results indicate that activity associated with memory for intact shapes, like perception, produces retinotopic activity in LOC.

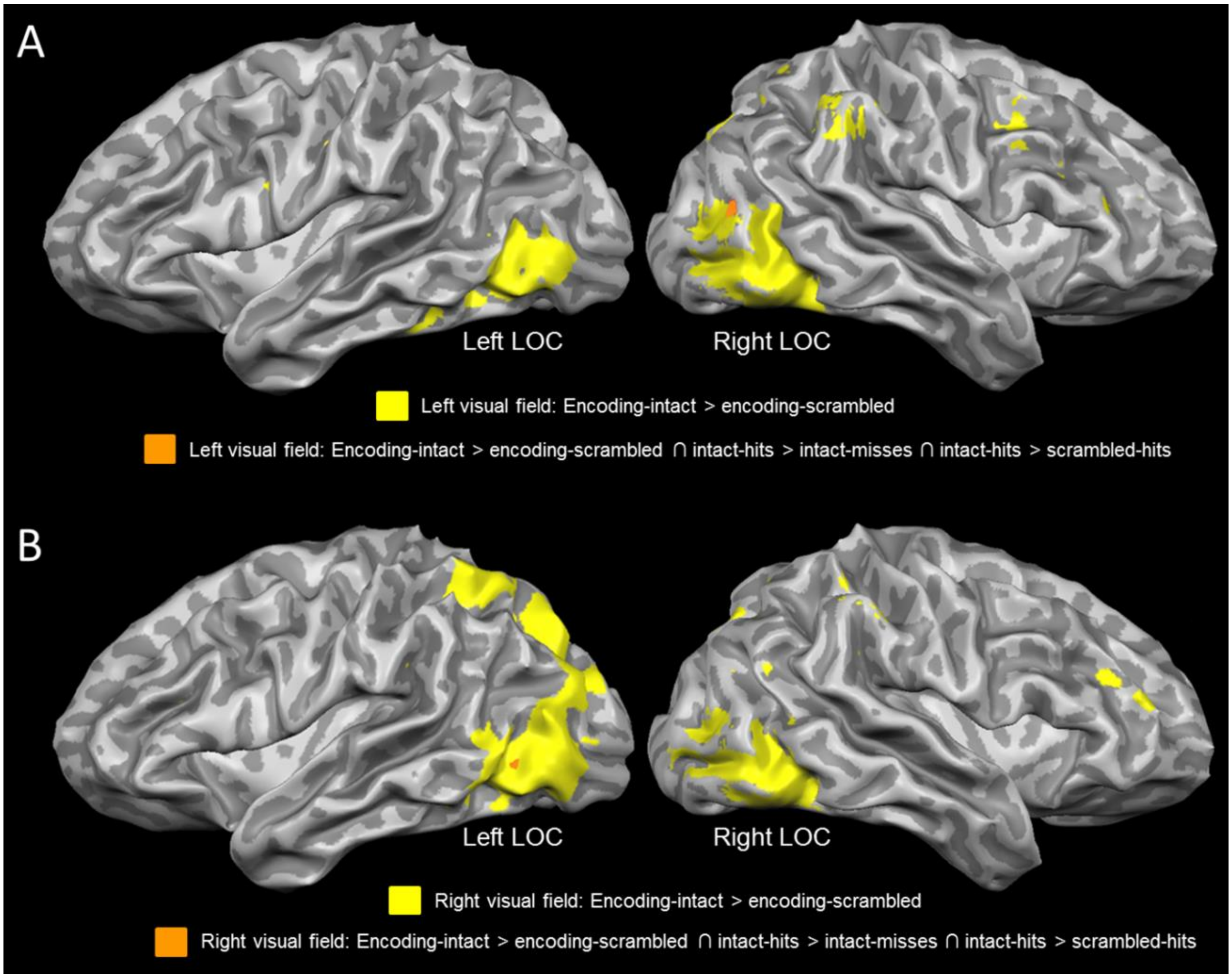

Figure 4. Memory for lateralized intact shapes activates contralateral LOC. (A) LOC activity from left visual field shape perception/encoding (encoding-left -intact > encoding-left -scrambled), shown in yellow, and the conjunction of left visual field shape perception/encoding, conscious intact shape retrieval (intact-left-hits > intact-left-misses), and accurate intact shape retrieval (intact-left-hits > scrambled-left-hits), shown in orange (key at the bottom). (B) LOC activity from right visual field shape perception/encoding (encoding-right-intact > encoding-right-scrambled), shown in yellow, and the conjunction of right visual field shape perception/encoding, conscious intact shape retrieval (intact-right-hits > intact-right-misses), and accurate intact shape retrieval (intact-right-hits > scrambled-right-hits), shown in orange (key at the bottom).

Scrambled Shape Retrieval

As detailed below, previous studies have implicated LOC in the perception of non-intact shapes under certain task conditions (e.g., Ferber et al., 1995; Grill-Spector et al., 1998; Mendola et al., 1999; Stanley & Rubin, 2003). As such, it is possible that memory for scrambled shapes could have also produced activity in LOC to some degree. To determine if that was the case in the present study, we conducted a conjunction of perception/encoding of intact versus scrambled shapes (encoding-intact > encoding-scrambled) and accurate versus inaccurate retrieval of scrambled shapes (scrambled-hits > scrambled-misses). This conjunction did reveal activity in LOC (Figure 5; Table 2).

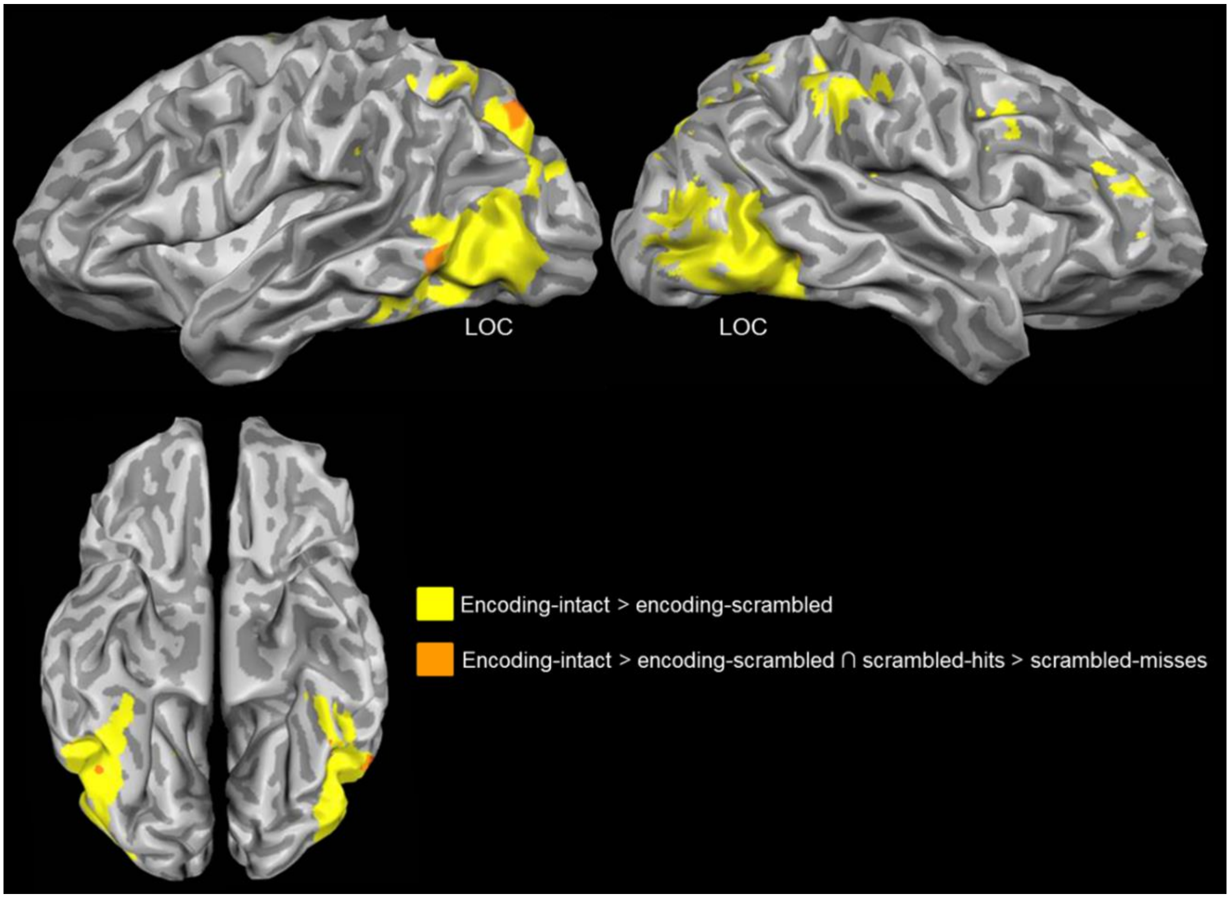

Figure 5. Memory for scrambled shapes activates LOC. LOC activity associated with shape perception/encoding (encoding-intact > encoding-scrambled), shown in yellow, and the conjunction of shape perception/encoding and scrambled shape retrieval (scrambled-hits > scrambled-misses), shown in orange (key to the bottom right).

Discussion

In the present study, we found that memory for shape produced activity in the same regions associated with perception/encoding of shape information. These results extend previous feature-specific memory reactivation findings, which correspond to motion-, color-, and spatial location-specific information (Karanian & Slotnick, 2014; Simmons et al., 2007; Slotnick, 2009a; 2009b; Slotnick & Thakral, 2011; Ueno et al., 2009), and provide further support for the constructive memory framework.

As mentioned previously, anatomically and functionally distinct regions LO and pFs have been identified within LOC. More anterior regions of LO appear to be more involved in complex shape processing/representation and spatial analysis than posterior regions of LO, which are more sensitive to lower-level features like orientation (Larsson & Heeger, 2006; Sayres & Grill-Spector, 2008; Silson et al., 2013). In the present study, we found that our LOC activations spanned both anterior and posterior regions of LO and pFs. This suggests that both lower-level and higher-level shape processing regions contribute to the construction of memory for shape information.

Previous work has demonstrated that perceptual processing of shape information produces retinotopic activity LOC (Hemond et al., 2007; McKyton & Zohary, 2007; Niemeier et al., 2004; Sayres & Grill-Spector, 2008). The present results indicate that memory for lateralized shape information activates contralateral LOC, which replicates previous spatial memory findings (Slotnick, 2009b) and can be assumed to reflect the specific reinstatement of perception/encoding activity.

To localize a feature-specific sensory processing region, it is standard to contrast perception/encoding of feature-specific items and perception/encoding of baseline items. Then, to determine whether sensory reactivation occurred, retrieval contrasts are overlaid with the perception/encoding contrast and overlap indicates reactivation. The constructive memory framework predicts that retrieval of feature-specific information should reactivate feature-specific perception/encoding regions, whereas retrieval of baseline items should not activate feature-specific perception/encoding regions. Previous feature-specific memory results have been in line with this prediction (Simmons et al., 2007; Slotnick, 2009a; 2009b; Slotnick & Thakral, 2011; Ueno et al., 2009). For example, memory for colored items reactivated color perception/encoding region V8, while memory for gray items did not activate this region (Slotnick, 2009a), and memory for moving items reactivated motion processing region MT+, while memory for stationary items did not activate this region (Slotnick & Thakral, 2011). The present results support this body of work in that memory for intact shapes preferentially activated LOC.

Although LOC was primarily activated by intact shapes, this region was also activated to some degree by scrambled shapes. Previous work has shown that LOC responds to illusory contours (Mendola et al., 1999; Stanley & Rubin, 2003). Another study manipulated the degree to which images were scrambled and found that LOC remained significantly more active for mildly scrambled images as compared to highly scrambled images (Grill-Spector et al., 1998), which suggests scrambled images can require some degree of shape processing. Previous research has also demonstrated that scrambled shapes can produce activity in LOC under particular task conditions. In one study, scrambled items were presented in motion, where all scrambled fragments moved in the same direction and at the same speed to induce figure/ground segregation (Ferber et al., 2005). As a result of the motion-induced figure/ground segregation, LOC processed each scrambled item and continued to process it even after the motion stopped. It was concluded that this particular manipulation induced a shape illusion that engaged LOC. These results suggest that, under certain conditions, LOC is capable of processing more than well-defined closed-loop intact shapes and objects. In the present paradigm, participants were tasked to actively encode both intact shapes and scrambled shapes. Thus, it is possible that participants encoded scrambled shapes as cohesive units, as compared to other perceptual studies in which participants only passively viewed stimuli. Such task differences may explain, in part, why LOC activity was observed during successful retrieval of scrambled shapes in the present study. Future research will be needed to determine the degree to which the LOC response to scrambled items is mediated by task or stimulus factors.

The present results show that memory for shape activates shape processing region LOC. These results complement previous findings that memory for feature-specific information reactivates the corresponding feature processing regions and provide compelling support for the view that retrieval is constructive in nature.

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Tables

Table 1. Memory for intact shapes reactivates LOC

Region	x	y	z	Cluster Size (mm^3)
Encoding-intact > encoding-scrambled ∩ intact-hits > intact-misses				
pFs	35	-41	-21	81
pFs	29	-45	-15	297
pFs	40	-50	-21	486
pFs	-42	-53	-17	8,154
pFs	-49	-65	-18	621
LO	50	-51	-9	54
LO	-34	-62	-3	54
LO	-55	-65	-4	243
LO	33	-68	9	54
LO	-35	-70	-2	1,890
LO	-43	-74	-6	324
LO	38	-77	6	675
Encoding-intact > encoding-scrambled ∩ intact-hits > scrambled-hits				
pFs	-41	-73	-15	1,458
pFs	-38	-66	-10	1,134
pFs	-36	-54	-12	243
LO	42	-50	-9	54
LO	36	-51	3	351
LO	47	-53	0	351
LO	50	-56	0	189
LO	36	-56	0	81
LO	-43	-63	6	108
LO	-37	-65	-2	3,969
LO	38	-73	9	19,359
LO	-43	-77	-6	297
LO	-39	-81	-2	5,238
LO	-35	-87	12	756
LO	-34	-88	3	513
Encoding-intact > encoding-scrambled ∩ intact-hits > intact-misses ∩ intact-hits > scrambled-hits				
pFs	-46	-53	-18	108
LO	-34	-62	-3	54
LO	-55	-65	-4	243
LO	-35	-69	0	702
LO	33	-68	9	54
LO	38	-77	6	135

Talairach coordinates (x, y, z) refer to the center of each activation.

Table 2. Memory for scrambled shapes activates LOC

Region	x	y	z	Cluster Size (mm^3)
Encoding-intact > encoding-scrambled ∩ scrambled-hits > scrambled-misses				
pFs	26	-44	-15	54
pFs	-40	-50	-15	27
pFs	41	-56	-18	108
pFs	41	-59	-15	54
pFs	-40	-60	-15	54
pFs	-49	-68	-12	162
LO	52	-50	-3	81
LO	-56	-61	-2	7,479
LO	36	-83	0	54

Talairach coordinates (x, y, z) refer to the center of each activation.

CHAPTER 2.2: FALSE MEMORY FOR SHAPE

False memories for shape activate the lateral occipital cortex

Jessica M. Karanian and Scott D. Slotnick

Under Review

Previous functional magnetic resonance imaging (fMRI) evidence has shown that true memory produces greater activity than false memory in early sensory cortex. Such evidence has given rise to the predominant view that false memories arise from higher-level conscious processing regions (e.g., the dorsolateral prefrontal cortex) rather than lower-level nonconscious processing regions (e.g., V1). We hypothesized that early sensory cortex may support false memories when stimuli are employed that are associated with conscious processing. In the present fMRI memory study, we assessed whether false memory for shape produces activity in the lateral occipital complex (LOC), a region that has been associated with conscious perception of and memory for shapes. During the encoding phase, participants viewed intact or scrambled colored abstract shapes. During the retrieval phase, colored disks were presented and participants indicated whether the corresponding shape was previously “intact” or “scrambled”. False memory for intact shapes, which was isolated by contrasting “intact”/scrambled items and “scrambled”/scrambled items, produced activity in LOC. This finding indicates that false memories can activate early sensory cortex under particular stimulus conditions, calls for a revision of the predominant view that only true memories activate early sensory cortex, and questions the potential use of fMRI results in the courtroom.

Functional magnetic resonance imaging (fMRI) studies have investigated the neural basis of false memories – instances in which you remember something that never actually occurred. Such studies have demonstrated that activity associated with true memories for visual information is greater than activity associated with false memories for visual information in regions of early sensory cortex, including Brodmann area (BA) 17 (i.e., V1; Okado & Stark, 2003; Stark, Okado, & Loftus, 2010; Dennis, Johnson, & Peterson, 2014) and BA18 (Okado & Stark, 2003; Stark et al., 2010; Dennis, Bowman, & Vanderkar, 2012; Karanian & Slotnick, 2014; Dennis et al., 2014). Highlighting this apparent dissociation between true memory and false memory activity in early visual regions, false memory contrasts (e.g., false memory > correct rejection) have failed to reveal activity in BA17 (Heun, Jessen, Klose, Erb, Granath, & Grodd, 2000; Cabeza, Rao, Wagner, Mayer, & Schacter, 2001; Hofer et al., 2007; Marchewka, Brechmann, Nowicka, Jednorog, Scheich, & Grabowska, 2008; Dennis, Kim, & Cabeza, 2008; Stark et al., 2010; Iidaka, Harada, Kawaguchi, & Sadato, 2012; Dennis et al., 2012; Gutchess & Schacter, 2012; Dennis et al., 2014; Karanian & Slotnick, 2014) and BA18 (Cabeza et al., 2001; Hofer et al., 2007; Dennis et al., 2008; Marchewka et al., 2008; Iidaka et al., 2012; Dennis et al., 2012; Dennis et al., 2014; but, see Heun et al., 2000; Karanian & Slotnick, 2014; Stark et al., 2010; Gutchess & Schacter, 2012). The preceding results have given rise to the current view that true memories, but not false memories, are underpinned by activity in early sensory cortex.

Of present interest, processing in early sensory cortex (e.g., V1) is believed to be largely nonconscious (e.g., Crick & Koch, 1995; Tong, 2003), which is thought to be why false memories, which reflect conscious processing, have not been associated with these regions (Slotnick & Schacter, 2004; 2006; Stark et al., 2010). Instead, false memories have been associated with activity in higher-level conscious processing regions, including late visual regions, the prefrontal cortex, and language processing regions (e.g., Dennis et al., 2012; Karanian & Slotnick, 2014; Okado & Stark, 2003; Slotnick & Schacter, 2004). This pattern of results has also been observed in other regions of early sensory cortex. For instance, in a previous fMRI study (Karanian & Slotnick, 2014), we assessed activity in motion processing cortex (MT+) during true memory and false memory for moving shapes. We found that true memory for motion, but not false memory for motion, activated MT+. Instead, false memory for motion was associated with activity in the language processing regions. These results provide further support for the commonly observed finding that false memories are not associated with activity in regions of early sensory cortex.

We hypothesize that the previously reported pattern of true memory, but not false memory, activity in early sensory cortex may have been due to the nonconscious processing that typically occurs in the early cortical visual regions that have been evaluated (i.e., V1, MT+; Ungerleider & Mishkin, 1982; Goodale & Milner, 1992; Crick & Koch, 1995; Tong, 2003). By contrast, another region within early sensory cortex, the lateral occipital complex (LOC), plays a critical role in the conscious processing of shape and object stimuli (Kourtzi & Kanwisher, 2000; Grill-Spector, Kushnir, Hendler, & Malach, 2000; Deshpande, Hu, Lacey, Stilla, & Sathian, 2010; Karanian & Slotnick, 2015). As LOC is associated with conscious shape/object processing, we hypothesize that false memory for shapes would activate LOC, which would challenge the predominant view that false memories are not associated with activity in early sensory cortex. To test this hypothesis, we employed an fMRI paradigm in which participants remembered intact shapes and scrambled shapes (Figure 1). To anticipate the results, false memory for intact shapes produced activity in LOC.

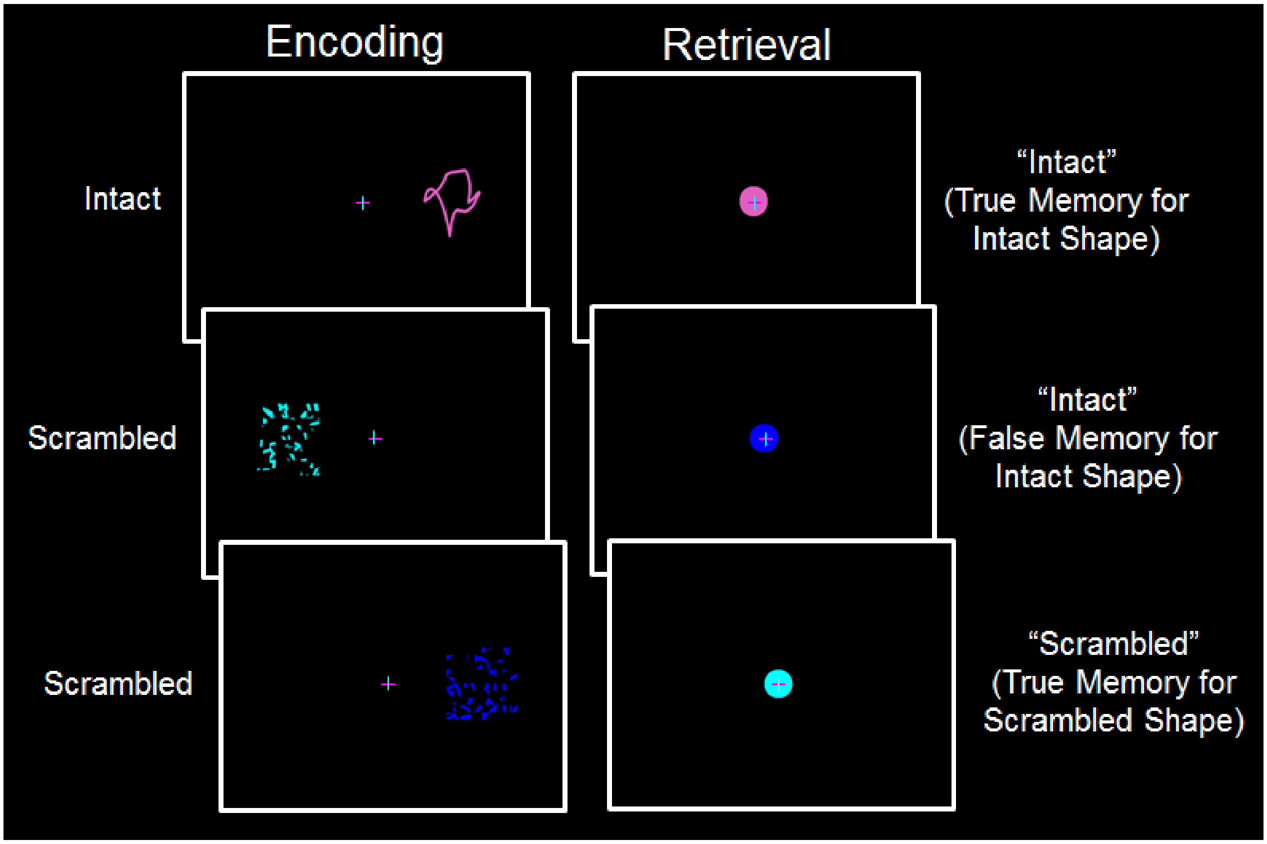

Figure 1. During encoding, uniquely colored intact or scrambled shapes were presented to the left or right of fixation. During retrieval, colored disks corresponding to the previously studied shapes were presented at fixation and participants classified each of the corresponding shapes as previously “intact” or “scrambled” (illustrative responses and item types are shown to the right).

Methods

Participants

Fourteen Boston College undergraduate students participated in the study (6 females, age range 19-22 years). Participants were right-handed, native English speakers, had normal or corrected-to-normal vision, and were compensated $10 for the behavioral training session and $25/hour (approximately $100) for the fMRI session. Informed and written consent was obtained before each session began. The Boston College Institutional Review Board approved the protocol.

Stimuli and procedure

Participants completed a behavioral training session, which included a one-fourth length memory run and one or two full-length memory runs. During fMRI, participants completed nine memory runs. During the encoding phase of each run, 16 uniquely colored intact or scrambled shapes spanning 4.6° of visual angle were presented in the left or right visual field with the nearest edge 2.5° of visual angle from fixation (Figure 1, left). Intact shapes were designed to minimize verbal encoding strategies (see Slotnick & Schacter, 2004). Each scrambled shape was created by superimposing a 10 x 10 grid over the bounding box of an intact shape and then each pixel was reassigned to a random location within the grid. Each shape was presented for 2.5 s with an inter-trial-interval of 3.0 s. Shape sets were randomized and presented sequentially five times. Shapes and colors were never repeated across runs. A Latin Square design was used to counterbalance shape sets (intact–left, intact–right, scrambled–left, scrambled–right) across participants. Participants were instructed to always maintain fixation and to remember each shape and its spatial location.

Immediately before the retrieval phase of each run, an instruction screen was presented for 8 seconds that reminded participants to maintain fixation and displayed the previously learned response mappings. During the retrieval phase of each run, 16 colored disks corresponding to the previously studied shapes were presented in random order at fixation (Figure 1, right). Each disk spanned 1.8° of visual angle and was presented for 3.5 s with an inter-trial interval of 7 to 10 s. Participants responded with their left hand to classify the shape corresponding to the colored disk as previously “intact” or “scrambled” in the “left” or “right” visual field via button presses. Participants made a subsequent “remember”–“know” response to characterize their subjective experience. “Remember”–“know” and spatial location responses were collapsed to maximize power. During both encoding and retrieval, no more than three items of a given type were sequentially presented and participants were instructed to maintain fixation.

Data were acquired using a Siemens 3 T Trio Scanner (Erlangen, Germany) with a 12-channel head coil. Functional images were acquired with an echo planar imaging sequence (TR = 2000 ms, TE = 30 ms, flip angle = 90°, field-of-view = 256 mm × 256 mm, acquisition matrix = 64 × 64, slices = 33, slice thickness = 4 mm; 4 mm isotropic resolution). Anatomic images were acquired with a magnetized prepared rapid gradient echo sequence (TR = 30 ms, TE = 3.3 ms, flip angle = 40°, field-of-view = 256 mm × 256 mm, acquisition matrix = 256 × 256, slices = 128, slice thickness = 1.33 mm; 1.33 × 1 × 1 mm resolution). Brain Voyager QX (Brain Innovation B.V., Maastrict, The Netherlands) was used to conduct the analysis. Pre-processing included slice-time correction, motion correction, and temporal filtering by removal of linear trends and components at or below 2 cycles per run length (using a general linear model to remove low frequency Fourier basis sets). Spatial smoothing was not conducted to maximize spatial resolution. Anatomic and functional images were transformed into Talairach space.

A random-effect general linear model was conducted. A canonical hemodynamic response function was convolved with the protocol of each event to produce each hemodynamic response model (i.e., a square wave defined by each event onset and the subsequent behavioral response) for each participant. Encoding trials were assumed to have durations of 2.5 s and no-response trials at retrieval were assumed to have durations of 3.5 s. The following event types were entered into the general linear model for the primary analysis: accurate subsequent memory for shape and spatial location, accurate subsequent memory for shape and inaccurate spatial memory for spatial location, inaccurate subsequent memory for shape and spatial location, accurate memory for shape and spatial location, accurate memory for shape and inaccurate memory for spatial location, inaccurate memory for shape and spatial location, no response, and a constant. That is, the general linear model included a separate regressor for no response trials and a constant. As we were only interested in memory for shape, we collapsed over spatial location to maximize power.

Activations were localized on the group average anatomic volume. An individual voxel threshold of $p < .001$ was enforced for all contrasts, whole-brain false discovery rate corrected for multiple comparisons to $p < .05$. Activations were projected onto a representative inflated cortical surface for display purposes (see Slotnick, 2005). Event-related activation timecourses were extracted from LOC (i.e., voxels within a 7 mm cube centered at each selected coordinate) within the time range of –2 to 12 s after stimulus onset (baseline corrected from –2 to 0 s). Statistical analysis was based on the peak amplitude of activity from 6 to 8 s after stimulus onset, the expected maximum of the hemodynamic response, to avoid violation of independence.

True memory for shape hits were defined as events where previously intact shapes were classified as "intact" (i.e., "intact"/intact) and true memory for shape misses were defined as events where previously intact shape were classified as "scrambled" (i.e., "scrambled"/intact). Analogous event types were assumed to reflect false memory for shape (i.e., "intact"/scrambled and "scrambled"/scrambled, respectively).

Results

We isolated shape processing activity by contrasting encoding/perception of intact shapes and encoding/perception of scrambled shapes *(intact shape encoding > scrambled shape encoding)*. As activity associated with shape encoding/perception was widespread (Figure 2, in yellow), LOC was anatomically localized to the lateral aspect of the occipital lobe (Karanian & Slotnick, 2015; Kourtzi & Kanwisher, 2000). The Talairach coordinates for LOC are consistent with previous findings (e.g., Grill-Spector et al., 1998; 2000).

To test for sensory-specific reinstatement of encoding-related activity during true memory for shape (i.e., hits > misses), we ran a conjunction of shape processing and true memory for shape *(intact shape encoding > scrambled shape encoding) ∩ ("intact"/intact > "scrambled"/intact)*, which revealed activity in LOC (Figure 2, top, in orange). To test our hypothesis that false memory for shape would activate LOC, we ran the analogous conjunction for false memory *(intact shape encoding > scrambled shape encoding)* ∩ *("intact"/scrambled > "scrambled"/scrambled)*, which also revealed activity in LOC (Figure 2, bottom, in orange).

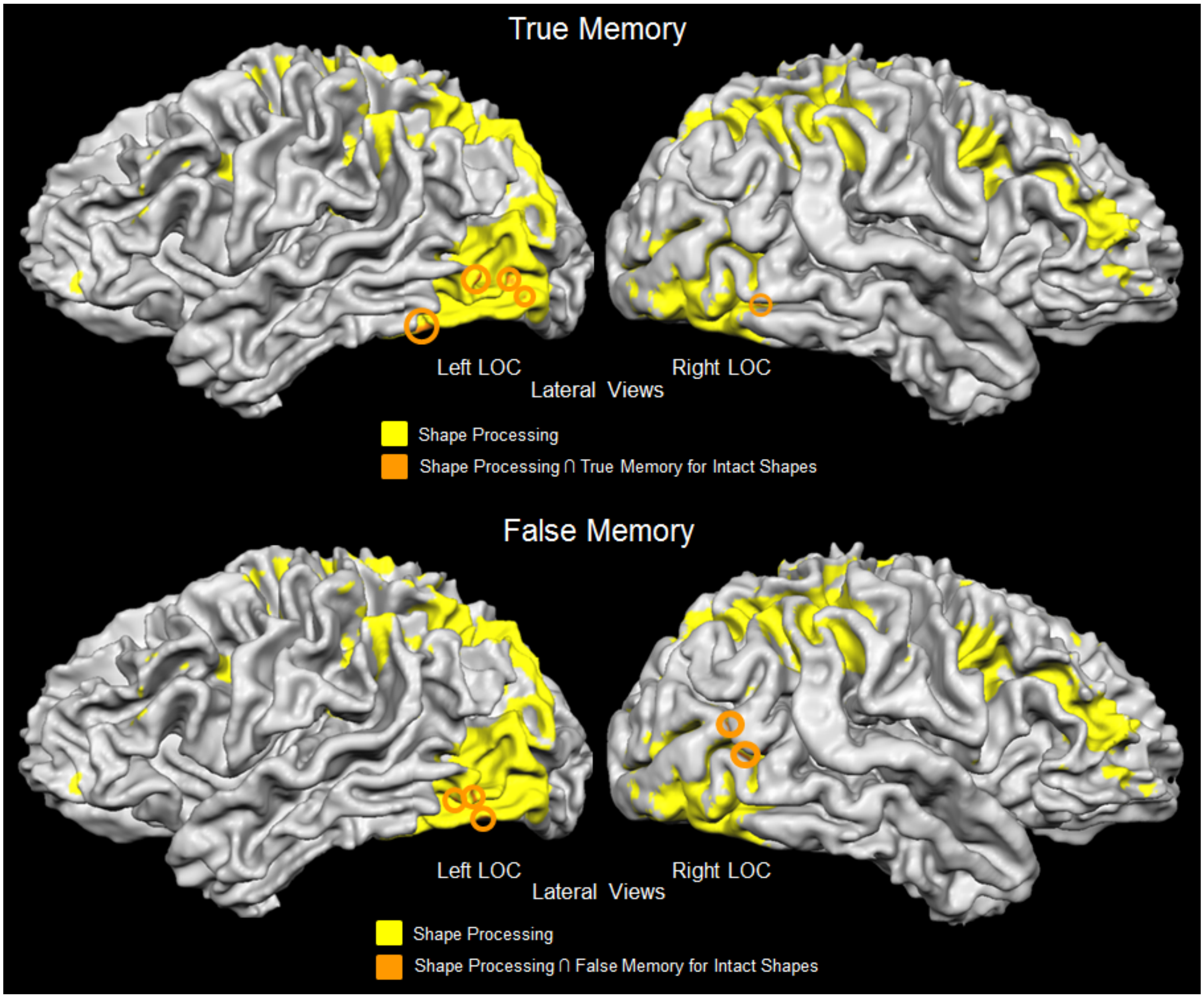

Figure 2. True memory and false memory activity in LOC. Shape processing activity is shown in yellow. Top, activity associated with true memory for shape is shown in orange (lateral views; key at the bottom). Activations within LOC are circled. Bottom, activity associated with false memory for shape is shown in orange (lateral views; key at the bottom).

To assess whether there were any regions of overlapping activity, we conducted a triple conjunction of shape processing, true memory for shape, and false memory for shape *(intact shape encoding > scrambled shape encoding)* ∩ *("intact"/intact > "scrambled"/intact)* ∩ *("intact"/scrambled > "scrambled"/scrambled)*. This conjunction revealed activity in only one sub-region of LOC (Figure 3, in orange). That is, the activations for true memory and false memory within LOC were almost completely distinct.

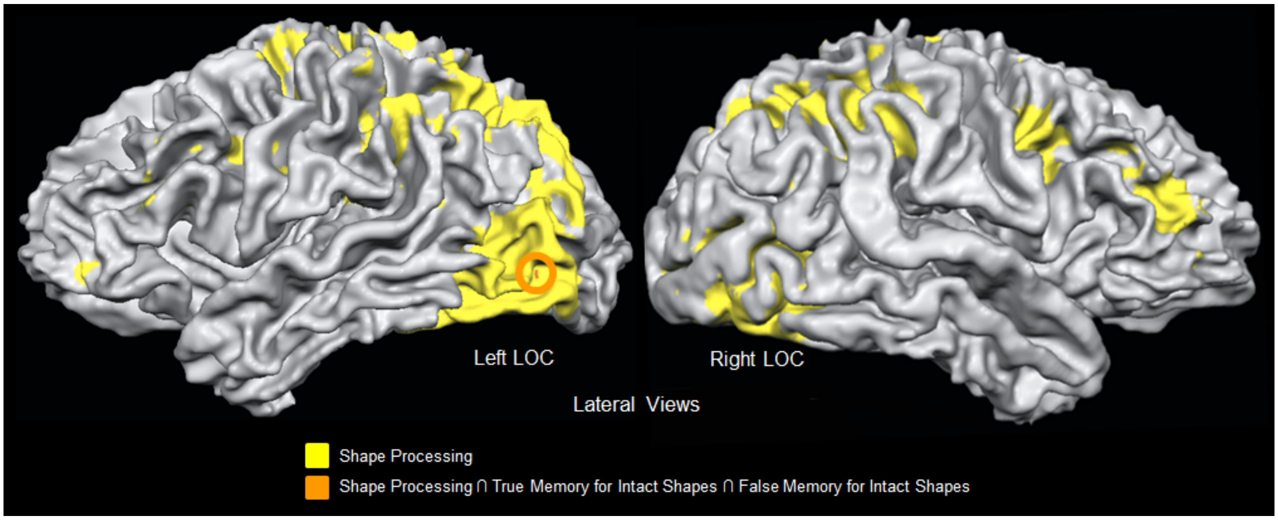

Figure 3. Overlapping true memory and false memory activity in LOC. Shape processing activity is shown in yellow. Activity associated with the conjunction of shape processing, true memory for shape, and false memory for shape is shown in orange (lateral views; key at the bottom). The activation within LOC is circled.

To replicate previous work in which true memory activates early sensory regions to a greater degree than false memories, we directly contrasted true memory for shapes and false memory for shapes. We ran a conjunction of shape processing and true memory versus false memory *(intact shape encoding* > *scrambled shape encoding)* ∩ *((“intact”/intact* > *“scrambled”/intact)* > *(“intact”/scrambled* > *“scrambled”/scrambled))*, which produced activity in several regions of LOC (Figure 4).

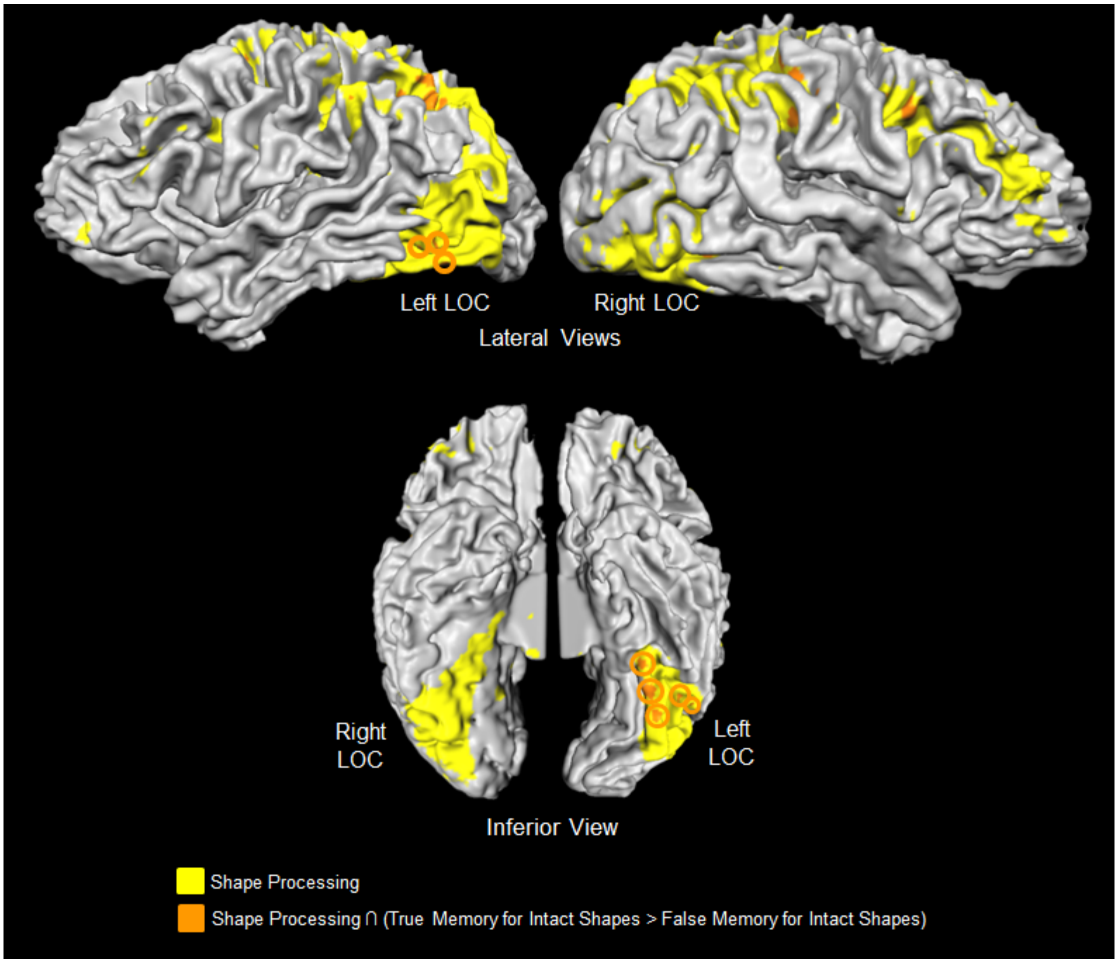

Figure 4. True memory versus false memory activity in LOC. Shape processing activity is shown in yellow. Activity associated with the conjunction of shape processing and (true memory for shape > false memory for shape) is shown in orange (key at the bottom). Activations within LOC are circled.

Discussion

The predominant view is that early sensory cortex is not involved in false memory construction. Instead, false memories have been commonly associated with activity in higher-level conscious processing regions such as late visual regions, the prefrontal cortex, and language processing regions. The present study investigated whether false memories could activate regions of the early sensory cortex under particular stimulus conditions. Specifically, we hypothesized that false memory for shape may be activate the LOC, given its a relatively conscious role in visual processing (e.g., Karanian & Slotnick, 2015; Ungerleider & Mishkin, 1982). Consistent with our hypothesis, we found that false memory for shape, like true memory for shape, activated LOC.

The present results are in direct contrast with what we observed in our previous study in which participants remembered whether items were previously moving or previously stationary (Karanian & Slotnick, 2014). Specifically, we found that true memory for motion, but not false memory for motion, activated motion processing region, MT+ (Karanian & Slotnick, 2014). To assess the apparent dichotomy between LOC and MT+, we extracted activity from the single LOC activation associated with true memory and false memory in the present study and compared this activation profile to the activation profile from MT+ in our previous study (Karanian & Slotnick, 2014). As shown in Figure 5, there was a significant region (MT+, LOC) by memory type (true, false) interaction ($p < .05$), which indicates that the involvement of early sensory cortical regions during false memory is dependent on stimulus type. Specifically, the magnitudes of true memory and false memory activity did not significantly differ in LOC ($p > .20$), but the magnitude of true memory activity was greater than the magnitude of false memory activity in MT+ ($p < .05$).

We propose that this region by memory type interaction reflects relatively nonconscious and conscious processing within MT+ and LOC, respectively. Specifically, MT+ is located within the ‘where’ pathway, which is thought to mediate largely nonconscious visual processing (e.g., Goodale & Milner, 1992; Ungerleider & Mishkin, 1982). Of additional relevance, two recent studies have suggested that MT+ plays a nonconscious role during memory for motion (Karanian & Slotnick, 2014; Thakral & Slotnick, 2014). By contrast, LOC is located within the ‘what’ pathway, which is thought to be associated with conscious experience of shape/object recognition (Goodale & Milner, 1992; Kourtzi & Kanwisher, 2000; Ungerleider & Mishkin, 1982). Highlighting its role in conscious processing, LOC activity has been correlated with behavioral performance during object recognition (e.g., Grill-Spector et al., 2000), and we recently found greater LOC activity during accurate than inaccurate memory for shapes (Karanian & Slotnick, 2015). Thus, in light of this nonconscious and conscious processing dichotomy observed between MT+ and LOC, the differential pattern of true versus false memory activity likely stems from the distinct functional processing that occurs within these regions of early sensory cortex.

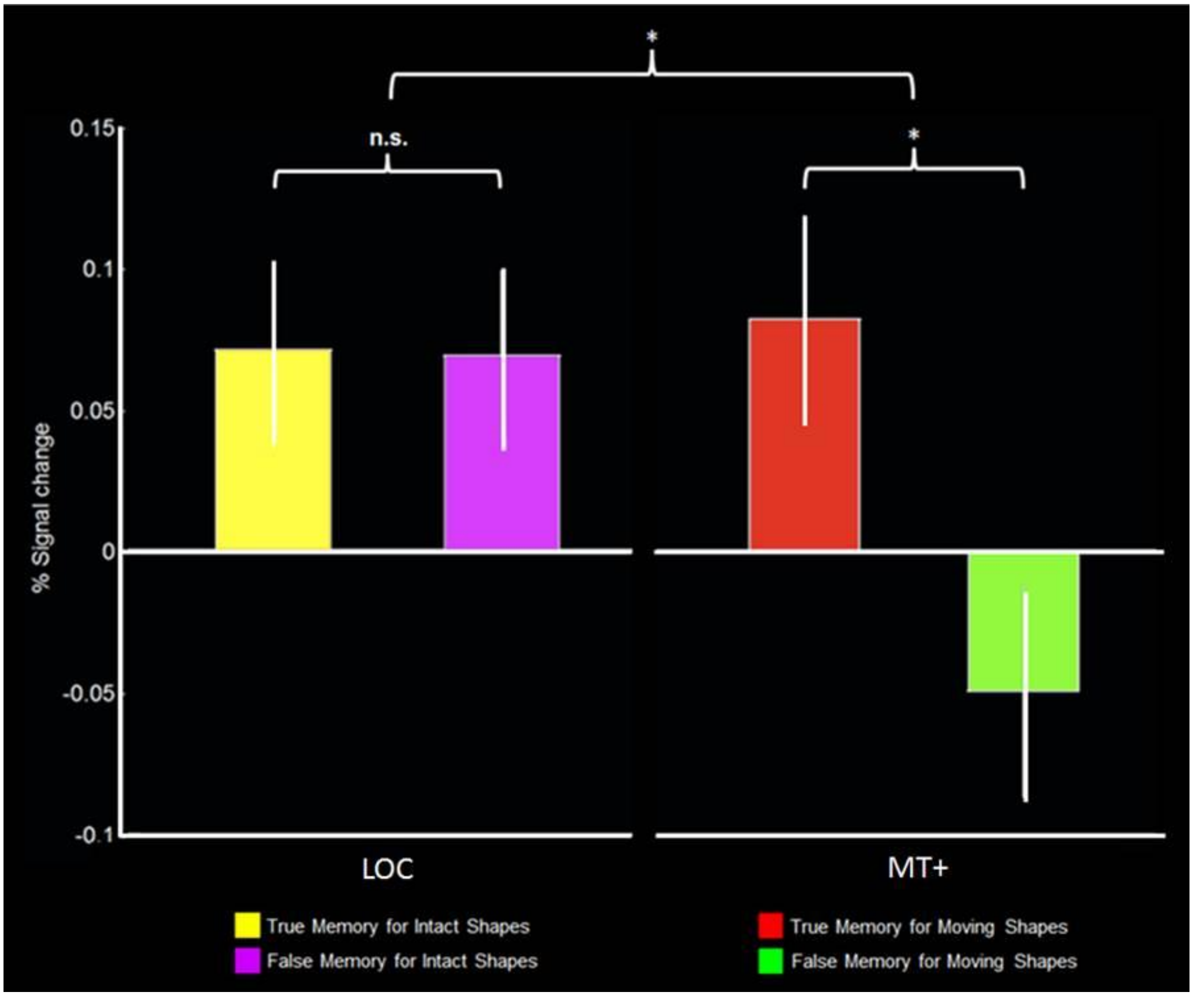

Figure 5. Brain region by memory type interaction. Left, activations associated with true memory for shape (in yellow) and false memory for shape (in purple) were extracted from the shape processing cortex, LOC (key at the bottom). Right (Karanian and Slotnick, 2014), activations associated with true memory for motion (in red) and false memory for motion (in green) were extracted from the motion processing cortex, MT+ (key at the bottom; mean ± 1 se shown; * = p < .05; n.s. = non-significant).

More broadly, our findings are in opposition to the predominant view that false memories are not underpinned by activity in early sensory cortical regions. It is noteworthy that three previous studies have reported false memory-related activity in BA17 / V1; however, such false memory activity may not reflect episodic memory activity given confounds within the contrasts employed. In two of these studies (Slotnick & Schacter, 2004; Garoff-Eaton, Slotnick, & Schacter, 2006), participants were presented with abstract shapes during the encoding phase. During the retrieval phase, old items, related items, and new items were presented, and participants classified each item as “old” or “new” (Slotnick & Schacter, 2004) or “old”, “similar”, or “new” (Garoff-Eaton et al., 2006). False memory activity was isolated by contrasting “old”/related items (i.e., false recognition of related items) and “new”/new items (i.e., correct rejections; Slotnick and Schacter, 2004) or by contrasting “old”/related items and “old”/new items (i.e., false recognition for unrelated items; Garoff-Eaton et al., 2006), both of which produced activity in left V1. However, these contrasts have an item type confound in that related items were compared to new items. Previous work has shown that related shapes, as compared to new shapes, produce increases in repetition priming-related activity within early visual regions (e.g., Slotnick & Schacter, 2006; for a review, see Thakral, Jacobs, & Slotnick, in press). Thus, the previously reported false memory-related activity in BA17/V1 in these two studies can be attributed to repetition priming. A third study (Okado & Stark, 2003) employed a paradigm in which audio words preceded either a picture of the word or a blank screen, which cued the participant to imagine an object that corresponded to the word. At retrieval, participants were presented with words from encoding and new words, and then distinguished if each word was previously paired with an object image, previously imagined, or new. In this paradigm, false memory was defined as incorrectly identifying a previously imagined object as previously seen. Okado and Stark (2003) contrasted false memory (“seen”/ imagined) versus correct rejections (“new”/new). Since false memory was induced by previous imagery, and imagery can activate regions of the early and late visual cortex (Slotnick, Thompson, & Kosslyn, 2005), it is conceivable that any V1 activity observed during false memory resulted from sensory reinstatement of the imagery experience at encoding. Thus, this false memory contrast cannot reliably distinguish whether visual activity resulted from nonconscious encoding-related reinstatement or from false memory-related activity.

The present findings that both true memory and false memory can produce activity in early sensory cortex are consistent with previous behavioral findings that true memory and false memory can be associated with similar subjective memorial experience. For instance, in one study, participants heard word lists (e.g., table, sit, legs, etc.) that were each related to a single critical nonpresented word (e.g., chair; Roediger & McDermott, 1995). False memories for critical nonpresented words (e.g., chair) and true memories for presented words (e.g., sit) were associated with similar rates of “remember” responses. This study and subsequent studies (see Lampinen, Neuschatz, & Payne, 1998; Payne, Neuschatz, Lampinen, & Lynn, 1997) have demonstrated that subjective sensory detail can be similar for true memories and false memories. The present results indicate that such detailed subjective experience during false memories may be mediated by stimulus-specific activity in early sensory cortex.

Replicating previous work, we also found that true memory activity was greater than false memory activity in early sensory cortex (i.e., LOC). These findings are consistent with the sensory reactivation view, which stipulates that the original features/sensory information associated with an encoding experience will be reinstated at retrieval (e.g., Gottfried, Smith, Rugg, & Dolan, 2004; Karanian & Slotnick, 2014; 2015; Schacter, Norman, & Koustaal, 1998; Slotnick, 2009a; 2009b; Slotnick & Thakral, 2011; Wheeler, Petersen, & Buckner, 2000). Thus, it could be assumed that the differential sensory activity observed during true memories versus false memories results from sensory reactivation, as only true memories are associated with the original encoding experience. This assumption has motivated the proposal that retrieval-related activity in early sensory cortex could serve as an objective assessment of memory accuracy in legal contexts, similar to a lie-detector test (for a review, see Schacter & Loftus, 2013). However, in the current experiment, we found false memory activity in early sensory cortex, which indicates that the presence or absence of early sensory cortical activity should not be considered a reliable indicator of memory accuracy. These results highlight the potential hazards of relying on fMRI results in legal settings.

The present finding that false memory for shapes activates LOC suggests that early sensory cortex may underpin the construction of false memories under particular stimulus conditions. Such evidence challenges the predominant view that false memory is only mediated by higher-level conscious processing regions (e.g., the dorsolateral prefrontal cortex). Future research will be needed to assess whether such effects are observed in other early sensory processing regions within the ventral processing stream. For instance, we predict that false memory for color will activate color processing region V8. Another future line of research could employ tasks that induce conscious processing in early sensory cortex, such as spatial memory tasks that have been shown to produce conscious processing in V1 (Thakral, Slotnick, & Schacter, 2013), to assess whether false memory can activate early sensory cortex under those task conditions. Critically, the present finding that false memories can activate early sensory cortex calls for a revision of the predominant view that only true memories activate these regions.

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PART 2

THE ROLE OF THE PARAHIPPOCAMPAL CORTEX DURING FALSE MEMORY

CHAPTER 3.1:

False memory for context activates the parahippocampal cortex

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Previous studies have reported greater activity in the parahippocampal cortex during true memory than false memory, which has been interpreted as reflecting greater sensory processing during true memory. However, in these studies, sensory detail and contextual information were confounded. In the present fMRI study, we employed a novel paradigm to dissociate these factors. During encoding, abstract shapes were presented in one of two contexts (i.e., moving or stationary). During retrieval, participants classified shapes as previously “moving” or “stationary”. Critically, contextual processing was relatively greater during false memory (“moving” responses to stationary items), while sensory processing was relatively greater during true memory (“moving” responses to moving items). Within the medial temporal lobe, false memory versus true memory produced greater activity in the parahippocampal cortex, whereas true memory versus false memory produced greater activity in the hippocampus. The present results indicate that the parahippocampal cortex mediates contextual processing rather than sensory processing.

Medial temporal lobe sub-regions play integral roles during true memory and false memory. Cabeza, Rao, Wagner, Mayer, and Schacter (2001) were the first to assess whether activity in medial temporal lobe sub-regions distinguished between true memory and false memory. They implemented a modified version of the Deese-Roediger-McDermott paradigm (Deese, 1959; Roediger & McDermott, 1995). At study, participants watched video clips of speakers reading categorized word lists (e.g., water, freeze, wet, etc.) that were each related to a critical nonpresented word (e.g., cold). At test, participants were presented with old items, related items, and new items during functional magnetic resonance imaging (fMRI). True memory (i.e., old item hits) produced greater activity than false memory (i.e., related item false alarms) in the parahippocampal cortex. Cabeza et al. (2001) postulated that this parahippocampal cortex activity reflected recovery of sensory information, as true memories have greater sensory detail than false memories (Mather, Henkel, & Johnson, 1997; Norman & Schacter, 1997). Subsequent studies that employed categorized picture lists (Gutchess & Schacter, 2012) and picture perception or imagery (Okado & Stark, 2003) also reported greater parahippocampal cortex activity during true memory than false memory, and a recent study that used pairs of pictures with the same verbal label observed greater parahippocampal cortex activity during true recollection than false recollection (Abe et al., 2013). To our knowledge, the opposite comparison – false memory versus true memory – has never produced activity in the parahippocampal cortex (but see, Stark, Okado, & Loftus, 2010; Dennis, Bowman, & Vandekar, 2012).

The preceding evidence suggests that activity in the parahippocampal cortex may always be greater during true memory than false memory. As mentioned previously, this may be because true memories are associated with greater sensory detail, which is consistent with the hypothesis that the parahippocampal cortex mediates visual spatial processing such as visual size or spatial layout (Epstein & Kanwisher, 1998; Epstein & Ward, 2010; Troiani, Stigliani, Smith, & Epstein, 2014; note that all of the protocols described above involved pictorial stimuli).

Alternatively, it has been hypothesized that the parahippocampal cortex mediates contextual processing such as the source of previously presented items (Eichenbaum, Yonelinas, & Ranganath, 2007; Eichenbaum, Sauvage, Fortin, Komorowski, & Lipton, 2012; Ranganath, 2010; Slotnick, 2013). Critically, both sensory detail and contextual information was greater during true memory than false memory in the above-mentioned memory studies (i.e., these factors were confounded). Therefore, the role of the parahippocampal cortex during true memory and false memory is uncertain.

In the present study, we aimed to dissociate sensory processing and contextual processing such that false memories would require greater contextual processing than true memories. During encoding, abstract shapes were presented in either one of two contexts (i.e., in motion or stationary; Figure 1A). During retrieval, old items from encoding were presented at fixation and participants identified the previous context of each item (i.e., “moving” or “stationary”; Figure 1B). True memory corresponded to a “moving” response to a previously moving item. False memory corresponded to a “moving” response to a stationary item (i.e., the incorrect generation of a detailed context), which is similar to the incorrect generation of a critical nonpresented word during the Deese-Roediger-McDermott paradigm (as opposed to a “stationary” response to a moving item, which is more aptly described as forgetting the feature of motion).

Of importance, item information and contextual information is sometimes integrated, particularly when the contextual information can be considered an item feature (cf., Staresina & Davachi, 2008; Diana, Yonelinas, & Ranganath, 2010). As such, true memories in the present paradigm can be assumed to be based on such integrated trials, which do not involve separate contextual processing, and other trials in which item and contextual information are processed separately. By contrast, all false memories reflect incorrect contextual assignment (i.e., incorrectly assigning a stationary item to the “moving” context/source). Thus, across all trials in the present paradigm, it can be assumed that false memories require a greater degree of contextual processing than true memories. If the parahippocampal cortex mediates sensory processing (Epstein & Kanwisher, 1998; Epstein & Ward, 2010; Troiani et al., 2014), then activity in this region will be greater for true memories than false memories, as true memories are associated with greater sensory detail. Alternatively, if the parahippocampal cortex mediates contextual processing (Eichenbaum et al., 2007, 2012; Ranganath, 2010; Slotnick, 2013), then activity in this region will be greater for false memories than true memories. That is, in the present paradigm, these hypotheses predict the opposite pattern of activity in the parahippocampal cortex.

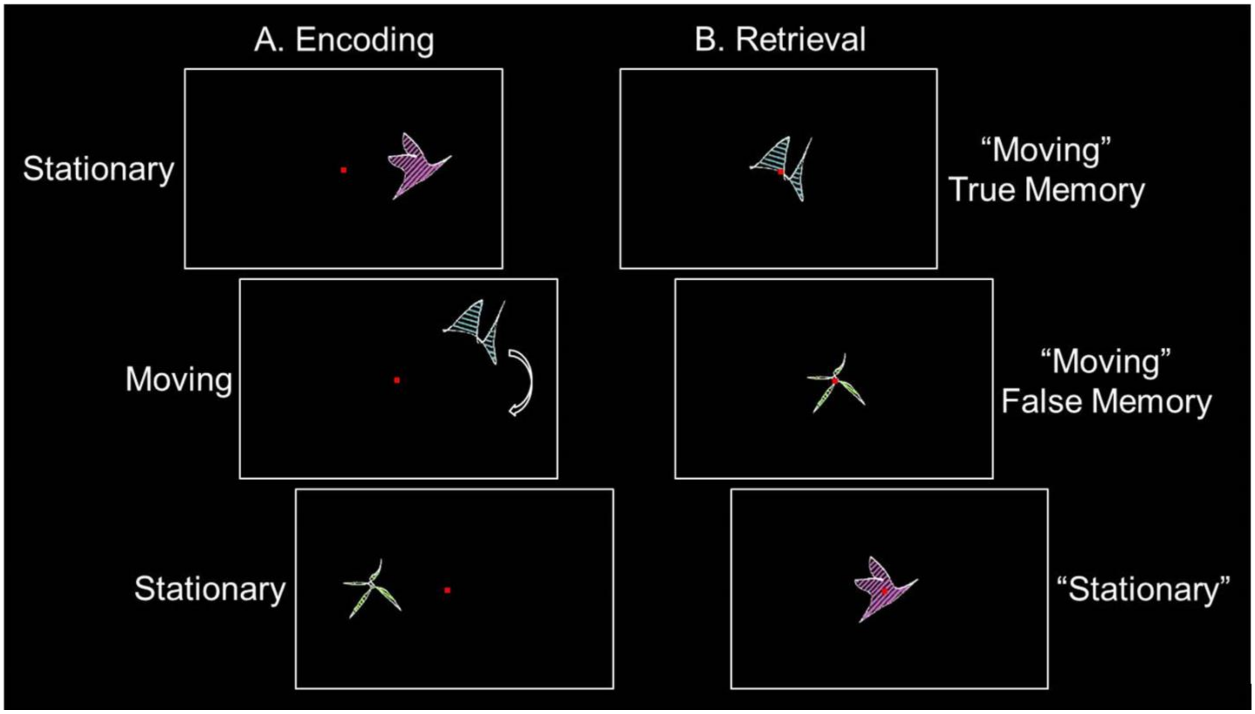

Figure 1. Stimulus protocol. (A) During encoding, moving and stationary shapes were presented to the left or right of fixation. (B) During retrieval, shapes were presented at fixation and participants classified each item as previously “moving” or “stationary”.

Method

Participants

Twelve Boston College students completed the study (9 females, age range 19-28 years). Participants were right-handed native English speakers with normal or corrected-to-normal vision. Each participant was compensated $10 for the behavioral training session and $25 per hour for fMRI. The Boston College Institutional Review Board approved the behavioral protocol and the Massachusetts General Hospital Institutional Review Board approved the fMRI protocol. Informed and written consent was obtained before each session.

Stimuli and procedures

Each participant completed a one-quarter length run and two full-length runs during the behavioral training session and six full-length runs during fMRI. They were instructed to always maintain fixation and remember whether each shape was moving or stationary and its spatial location. During the encoding phase of each full-length run, 24 abstract shapes were presented in the left or right visual field along an arc spanning ± 45° of polar angle from the horizontal meridian. Each shape spanned 4° of visual angle with the nearest edge 2° of visual angle from fixation. The shapes were designed to minimize verbal encoding strategies (for details on shape construction, see Slotnick & Schacter, 2004). Each shape was presented for 2.5 seconds with an inter-trial-interval of 3.0 seconds. Shape sets were repeated three times during encoding with each shape set randomized and presented sequentially. An equal number of shapes were stationary, at one of six equally spaced locations along the stimulation arc within each hemifield, or moving, smoothly traversing the entire stimulation arc in each hemifield with either upward or downward motion. In each run, all spatial locations and movement directions were presented equally often. Before the retrieval phase, an instruction screen was presented for 8 seconds that reminded participants to maintain fixation and displayed the response mappings. During each retrieval phase, the shapes from encoding were presented in random order at fixation for 3.5 seconds with an inter-trial-interval of 7 to 10 seconds. Participants pressed a response button with the fingers of their left hand to classify each shape as “previously moving in the left visual field”, “previously moving in the right visual field”, “previously stationary in the left visual field”, or “previously stationary in the right visual field”. Participants also made a subsequent “remember”-

“know” response to characterize their subjective experience. During encoding and retrieval, no more than three shapes of a given type were presented sequentially. Shapes were never repeated across runs. Sets of shapes (moving-left, moving-right, stationary-left, and stationary-right) were counterbalanced across participants using a Latin Square design.

Data acquisition and analysis

Imaging data were acquired on a Siemens 3 Tesla Trio Scanner with a standard head coil (Erlangen, Germany). Functional images were acquired with an echo planar imaging sequence (TR = 2000 ms, TE = 20 ms, flip angle = 90°, field-of-view = 256 × 256 mm^2, acquisition matrix = 64 × 64, slices = 33, slice thickness = 4 mm, 4 mm isotropic resolution). Anatomic images were acquired with a magnetized prepared rapid gradient echo sequence (TR = 30 ms, TE = 3.3 ms, flip angle = 40°, field-of-view = 256 × 256 mm^2, acquisition matrix = 256 × 256, slices = 128, slice thickness = 1.33 mm, 1.33 × 1 × 1 mm resolution). Analyses were conducted using Brain Voyager QX (Brain Innovation B.V., Maastricht, The Netherlands). Voxels were resampled at 3 mm^3. Pre-processing included slice-time correction, motion correction, and temporal filtering by removal of linear trends and components at or below 2 cycles per run length (using a general linear model to remove low frequency Fourier basis sets). To maximize spatial resolution, spatial smoothing was not conducted. Functional and anatomic images were transformed into Talairach space.

To maximize power, unless stated otherwise, we collapsed over spatial location and remember-know responses. Activations were localized on the group average anatomic volume. For all contrasts, an individual voxel threshold of $p < 0.001$ was enforced, false discovery rate corrected for multiple comparisons to $p < 0.05$. It should be mentioned that this method of correction for multiple comparisons limits the number of false positives but does not require a minimum spatial extent (Logan & Rowe, 2004). Only activations in the medial temporal lobe – the parahippocampal cortex, the hippocampus, the entorhinal cortex, and the perirhinal cortex –

were reported (other cortical activations are detailed in a separate manuscript; Karanian & Slotnick, 2014). Activations were localized based on the known anatomical distinctions of the medial temporal lobe (Insausti et al., 1998; Pruessner et al., 2000, 2002; Bernasconi et al., 2003; Malykhin et al., 2007).

Results

Behavioral accuracy for classifying moving items and stationary items was at an intermediate level (69.1 ± 3.0 % correct; mean ± 1 standard error). The contrast of false memory versus true memory for motion (“moving”/stationary items > “moving”/moving items) only produced activity in the parahippocampal cortex (Figure 2A; Table 1, top). The contrast of true memory versus false memory for motion (“moving”/moving items > “moving”/stationary items) only produced activity in the hippocampus (Figure 2B; Table 1, bottom). None of the activations spanned more than one sub-region of the medial temporal lobe.

Previous evidence indicates that the parahippocampal cortex is associated with recollection to a greater degree than familiarity (for a review, see Slotnick, 2013). As such, it is possible that the parahippocampal activity during false memory reflected recollection rather than contextual processing. However, “remember” rates were significantly greater for true memories than false memories (t (11) = 2.35, $p < 0.05$), which rules out the possibility that there was a greater degree of recollection during false memory than true memory and indicates that activity in this region reflected contextual processing.

An additional analysis was conducted to assess whether the present pattern of activity stemmed from differences in confidence/remember rates between true memory and false memory. To address this possibility, the contrast of false memory versus true memory for motion was conducted with only “remember” responses, which produced the identical pattern of activity described above. Therefore, the present pattern of results was not due to confidence differences between true memory and false memory.

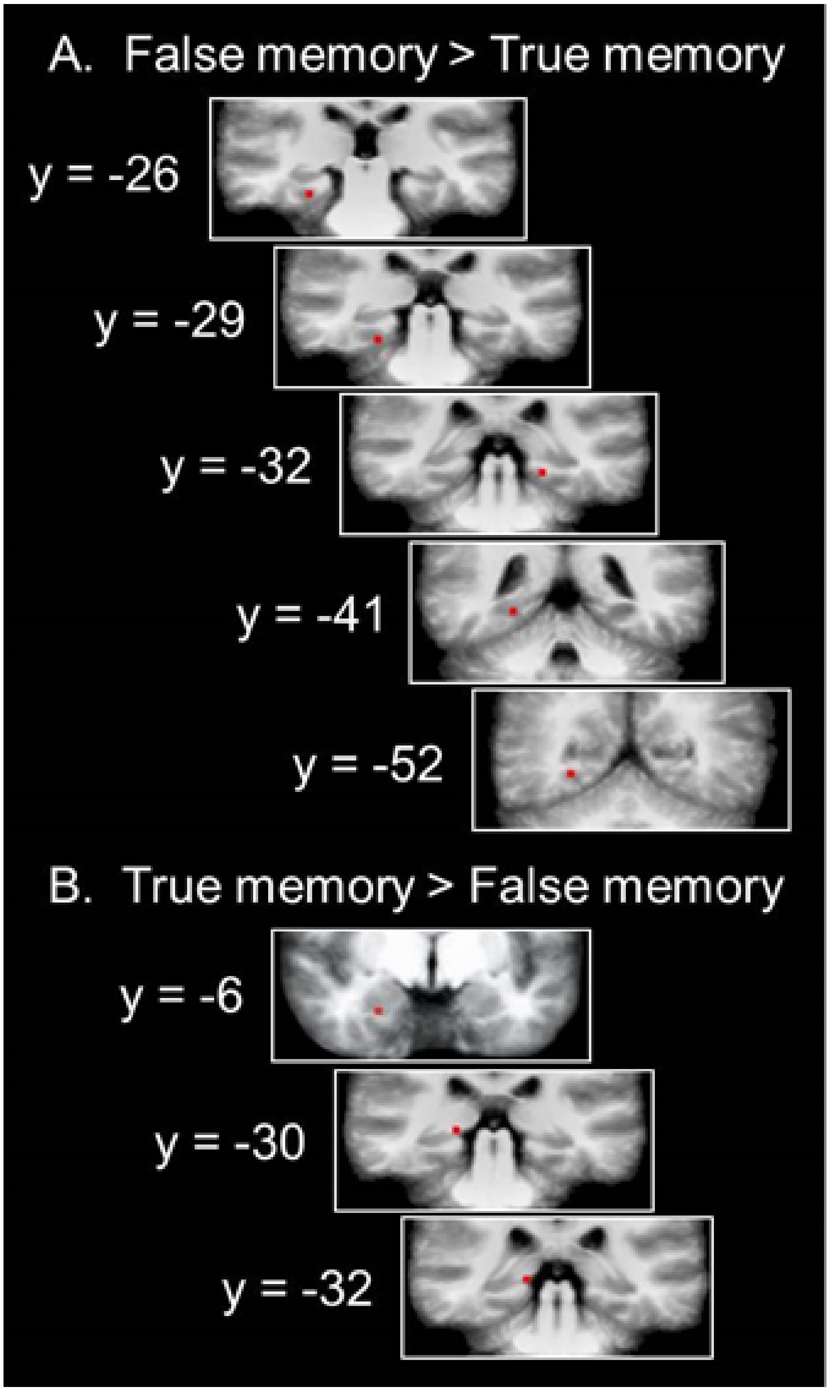

Figure 2. Medial temporal lobe activations. (A) False memory > true memory activations. (B) True memory > false memory activations. Each activation is shown in red on a coronal slice at the specified y-coordinate (the left hemisphere is on the left).

Discussion

Of direct relevance to the hypotheses of interest, we found that false memory versus true memory only produced activity in the parahippocampal cortex. This is the first time, to our knowledge, that false memory has produced greater activity than true memory in the parahippocampal cortex, as previous studies have only reported the opposite finding of greater true memory/recollection than false memory/recollection activity in this region (Cabeza et al., 2001; Okado & Stark, 2003; Gutchess & Schacter, 2012; Abe et al., 2013). The present results support the hypothesis that the parahippocampal cortex mediates contextual processing, which was greater for false memories than true memories in the present paradigm, rather than sensory processing, which was greater for true memories than false memories.

In the current study, false memories can be described from a source memory perspective. During encoding, items were presented in one of two contexts (i.e., moving or stationary). During retrieval, some previously stationary items were associated with little or no contextual information (e.g., due to lack of attention at encoding), and participants selected one of the two contexts/sources. Thus, in the present paradigm, an incorrect source response of "moving" to a previous stationary item was equivalent to a false memory for the context of motion. Along these lines, we contrasted incorrect spatial location/source responses ("right"/left items and "left"/right items) with correct spatial location/source responses ("right"/right items and "left"/left items), which only produced activity in the parahippocampal cortex. In a recent study (Abe et al., 2013), pictures were presented during encoding. During retrieval, same, similar, and new pictures were presented and participants made remember-know-new judgments. Familiarity-based false memories (i.e., "know same" responses to similar items) produced greater activity in the parahippocampal cortex than familiarity-based true memories (i.e., "know same" responses to same items). In this case, for weakly encoded items, participants may have selected the source (i.e., same or similar), where an incorrect source response of "know same" to a similar item can be described as a false memory. Therefore, in both the present study and this recent study (Abe et al., 2013), it appears more weakly encoded items yielded greater reliance on source processing – and produced greater activity in the parahippocampal cortex – during familiarity-based false memories than during familiarity-based true memories (see also, Kim & Cabeza, 2007). Future work will be needed to assess whether such familiarity-based false memories consistently activate the parahippocampal cortex to a greater degree than familiarity-based true memories.

More broadly, the parahippocampal cortex has been hypothesized to mediate either visual spatial processing (Epstein & Kanwisher, 1998; Epstein & Ward, 2010; Troiani et al., 2014) or contextual processing (Eichenbaum et al., 2007, 2012; Ranganath, 2010; Slotnick, 2013). Epstein & Ward (2010) argued that parahippocampal activation during source memory tasks may reflect spatial aspects of the encoding episode. A behavioral analysis was conducted to assess whether or not the activity observed in the parahippocampal cortex was driven by greater spatial processing for false memories compared to true memories. This analysis revealed that spatial location accuracy (i.e., memory for which side of the screen an item was previously presented) for true memory was significantly greater than spatial location accuracy for false memory ($t(11) = 2.77$, $p < 0.05$). Moreover, the false memory versus true memory fMRI contrast was conducted with spatial location accuracy constant (i.e., incorrect), and the identical pattern of results was obtained. Thus, in the present paradigm, false memory related parahippocampal activity appears to depend on contextual processing rather than spatial processing. Our findings are consistent with previous studies that reported parahippocampal activation during source memory for color (Ranganath et al., 2004; Diana et al., 2010) or task (word reading or imagery, Davachi, Mitchell, & Wagner, 2003; whether an item was animate or common, Kensinger & Schacter, 2006a), which do not involve spatial processing.

As mentioned previously, we assumed that a substantial proportion of true memories were based on the integration of item information and contextual information. This seems plausible as contextual information – whether a shape was moving or stationary – can be considered an item feature (see Staresina & Davachi, 2008). By comparison, during false memories item information and contextual information was never integrated because contextual assignment was incorrect. As a greater proportion of true memories than false memories can be assumed to be integrated, it follows that false memories required a relatively greater degree of contextual processing. Still, the assumption that true memories were based on relatively greater integration of item information and contextual information is a limitation of the present study that warrants further investigation.

We also found hippocampal activation was greater during true memory than false memory. Previous studies have also reported greater true memory than false memory activity in the hippocampus (Paz-Alonso, Ghetti, Donohue, Goodman, & Bunge, 2008; Giovanello, Kensinger, Wong, & Schacter, 2010). However, the majority of studies that have compared true memory and false memory have not observed differential activity in the hippocampus (Cabeza et al., 2001; Slotnick & Schacter, 2004; Kensinger & Schacter, 2006b; Stark et al., 2010). Furthermore, most studies have reported hippocampal activity during both true memory (Cabeza et al., 2001; Slotnick & Schacter, 2004; Kensinger & Schacter, 2006b; Kim & Cabeza, 2007; Paz-Alonso et al., 2008; Dennis et al., 2012; Gutchess & Schacter, 2012) and false memory (Cabeza et al., 2001; Slotnick & Schacter, 2004; Stark et al., 2010; Dennis et al., 2012; Gutchess & Schacter, 2012). Considered together, these results suggest that there may be somewhat greater hippocampal activation during true memories than false memories under certain conditions, but the hippocampus appears to be a critical region during the construction of both true memories and false memories (Schacter, Norman, & Koutstaal, 1998).

Of direct relevance to our aim, we dissociated sensory processing from contextual processing by employing a paradigm in which false memories reflected source memory. We found that parahippocampal activity tracked contextual processing during false memory rather than sensory processing during true memory. One limitation of the present study is that our paradigm involved memory for spatial location, thus our results are not completely immune from a visual spatial interpretation (see Epstein & Ward, 2010). The present results would be bolstered by eliminating any spatial memory component from the paradigm, such as in a source memory for color task where all the stimuli are presented centrally. This is a topic of future research.

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Table

Table 1. Medial temporal lobe activations.

Region	x	y	z	size (mm^3)
False memory > true memory				
Parahippocampal cortex	26	−26	−16	54
Parahippocampal cortex	22	−29	−15	27
Parahippocampal cortex	−19	−32	−9	27
Parahippocampal cortex	23	−41	−6	27
Parahippocampal cortex	25	−52	−3	54
True memory > false memory				
Hippocampus	23	−6	−21	27
Hippocampus	17	−30	0	27
Hippocampus	14	−32	0	54

Talairach coordinates (x, y, z) refer to the center of each activation.

CHAPTER 3.2

False memory for context and true memory for context similarly activate the parahippocampal cortex

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In Press at *Cortex*

The role of the parahippocampal cortex is currently a topic of debate. One view posits that the parahippocampal cortex specifically processes spatial layouts and sensory details (i.e., the *visual-spatial processing view*). In contrast, the other view posits that the parahippocampal cortex more generally processes spatial and non-spatial contexts (i.e., the *general contextual processing view*). A large number of studies have found that true memories activate the parahippocampal cortex to a greater degree than false memories, which would appear to support the visual-spatial processing view as true memories are typically associated with greater visual-spatial detail than false memories. However, in previous studies, contextual details were also greater for true memories than false memories. Thus, such differential activity in the parahippocampal cortex may have reflected differences in contextual processing, which would challenge the visual-spatial processing view. In the present fMRI study, we employed a source memory paradigm to investigate the functional role of the parahippocampal cortex during true memory and false memory for contextual information to distinguish between the visual-spatial processing view and the general contextual processing view. During encoding, abstract shapes were presented to the left or right of fixation. During retrieval, old shapes were presented at fixation and participants indicated whether each shape was previously on the “left” or “right” followed by an “unsure”, “sure”, or “very sure” confidence rating. The conjunction of confident true memories for context and confident false memories for context produced activity in the parahippocampal cortex, which indicates that this region is associated with contextual processing. Furthermore, the direct contrast of true memory and false memory produced activity in the visual cortex but did not produce activity in the parahippocampal cortex. The present evidence suggests that the parahippocampal cortex is associated with general contextual processing rather than only being associated with visual-spatial processing.

In a large number of studies within the field of perception, the parahippocampal cortex has been associated specifically with visual-spatial processing. For instance, the parahippocampal cortex has been shown to play a critical role in scene perception, navigation through space, and spatial representation (e.g., Aguirre, Detre, Alsop, & D'Esposito, 1996; Aguirre & D'Esposito, 1998; Epstein & Kanwisher, 1998; Epstein, Harris, Stanley, & Kanwisher, 1999; Janzen, Wagensveld, & van Turennout, 2007; Epstein, 2008; Epstein & Ward, 2010; Mullally & Maguire, 2011; Troiani, Stigliani, Smith, & Epstein, 2014). Such evidence has contributed to the view that the primary function of the parahippocampal cortex is to process visual-spatial information (i.e., the *visual-spatial processing view*; Epstein & Ward, 2010).

Within the field of memory, there is evidence that the parahippocampal cortex plays a critical role more broadly in contextual processing, as indicated by its involvement in recollection, associative memory, and source memory (e.g., Davachi, Mitchell, & Wagner, 2003; Ranganath, Yonelinas, Cohen, Dy, Tom, & Esposito, 2004; Eichenbaum, Yonelinas, & Ranganath, 2007; Tendolkar et al., 2008; Ranganath, 2010; Slotnick, 2013a, 2013b; Wang, Yonelinas, & Ranganath, 2013). For instance, in one study, activity in the parahippocampal cortex was correlated with the amount of contextual information retrieved (Tendolkar et al., 2008). Images were presented in varying shades of red or green during the encoding phase. During retrieval, old and new gray images were presented and participants made old-new recognition judgements and then provided two context memory judgments for old items. They identified whether images were previously red or green (i.e., context judgment 1) and identified the particular shade of red or green (i.e., context judgment 2). Analysis of retrieval-related activity in the parahippocampal cortex revealed a linear increase based on the amount of context information retrieved (i.e., item and no context < item and 1 context < item and 2 contexts). Such evidence provides strong support for the view that the parahippocampal cortex plays a critical role in the retrieval of contextual information. However, many memory studies have employed paradigms that involved some degree of visual-spatial processing. Such paradigms have included scene processing (e.g., Duarte, Henson, & Graham, 2011; Davachi et al., 2003; Kahn, Davachi, & Wagner, 2004), spatial location processing (e.g., Cansino et al., 2002; Ross & Slotnick, 2008), and item size judgments (e.g., Hayes, Buchler, Stokes, Kragel, & Cabeza, 2011). As a result, proponents of the visual-spatial processing view have suggested that activity in the parahippocampal cortex observed during memory studies can be attributed to the inherent visual-spatial processing induced by the paradigms employed (see Epstein & Ward, 2010). However, other memory studies have shown that the parahippocampal cortex is associated with processing of non-spatial information (e.g., Kirwan & Stark, 2004; Ranganath et al., 2004; Diana, in press). For instance, Diana (in press) implemented a paradigm that was devoid of spatial processing. At encoding, participants were presented words and asked one of four different non-spatial questions related to each word (e.g., "*is this a noun or verb?"* or "*is this word common or uncommon?"*). At retrieval, participants completed an old-new recognition task for each item (i.e., the word) and then identified its associated context (i.e., the question). Directly challenging the visual-spatial processing view, non-spatial memories for context were associated with activity in the parahippocampal cortex. Such non-spatial evidence supports the *general contextual processing view* of the parahippocampal cortex.

Of direct relevance to the present investigation, a number of false memory studies have reported that the magnitude of activity in the parahippocampal cortex is greater during true memories than false memories (Cabeza, Rao, Wagner, Mayer, & Schacter, 2001; Kahn et al., 2004; Giovanello, Kensinger, Wong, & Schacter, 2009; Kim & Cabeza, 2007; Paz-Alonso, Ghetti, Donohue, Goodman, & Bunge, 2008; Dennis, Bowman, & Vandekar, 2012; Dennis, Johnson, & Peterson, 2014; Kurkela & Dennis, 2016). As true memories are often associated with greater visual-spatial detail than false memories (Mather, Henkel, & Johnson, 1997; Norman & Schacter, 1997; Slotnick & Schacter, 2004; Karanian & Slotnick, 2014a, under review), it is possible that differential activity observed in the parahippocampal cortex in previous studies (e.g., Cabeza et al., 2001; Kahn et al., 2004) reflected differences in visual-spatial processing during retrieval. However, in these false memory studies, contextual details were also greater for true memory than false memory; thus, the differential activity in the parahippocampal cortex could also reflect greater contextual processing during true memories than false memories. Specifically, in such old-new recognition paradigms, false memories were defined as endorsing a new item as "old", which means that false memories were associated with relatively less contextual processing than true memories, as new items are, by definition, devoid of previous contextual processing. Thus, it remains uncertain whether the true memory versus false memory differential activity in the parahippocampal cortex reflected differences in visual-spatial detail, which would provide support for the visual-spatial processing view, or differences in contextual processing, which would provide support for the general contextual processing view.

False memory studies have also employed source memory paradigms. In these paradigms, items are presented in a particular context/source during encoding (e.g., on a green background or on a red background), and then during retrieval participants identify the previous context (e.g., "green" or "red") of each item. The parahippocampal cortex has been associated with both true memory for contextual information (e.g., Davachi et al., 2003; Kensinger & Schacter, 2006; Ranganath et al., 2004) and false memory for contextual information (Stark, Okado, & Loftus, 2010; Karanian & Slotnick, 2014b), where old items from encoding were attributed to the wrong context (i.e., source misattribution errors). For instance, one study employed a paradigm in which items were presented either visually or auditorily during encoding (Stark et al., 2010). During retrieval, old items were presented and participants identified whether each was previously presented within the visual or auditory modality. False memories for the visual context (i.e., "visual"/auditory) were associated with activity in the parahippocampal cortex. Similarly, in a recent study, we employed a paradigm in which items were presented as either moving or stationary during encoding (Karanian & Slotnick, 2014b). During retrieval, old items were presented and participants identified the context of each item as previously “moving” or “stationary”. False memories for the context of motion (i.e., “moving”/stationary) produced activity in the parahippocampal cortex. The evidence from these studies suggests that false memory for context, like true memory for context, is associated with the parahippocampal cortex. Such evidence supports the general contextual processing view of the parahippocampal cortex. However, these studies are not immune from the visual-spatial processing account. For instance, it is conceivable that the visual context induced more visual-spatial processing than the auditory context (Stark et al., 2010) and that the motion context induced more visual-spatial processing than the stationary context (Karanian & Slotnick, 2014b). Thus, the role of the parahippocampal cortex during the construction of false memories for context remains uncertain.

In the present fMRI study, we employed a source memory paradigm to assess the role of the parahippocampal cortex during true memories for context and false memories for context to distinguish between the visual-spatial processing view and the general contextual processing view. Accordingly, we assessed the relative magnitude of activity in the parahippocampal cortex during true memories for context and false memories for context. Under the assumption that true memories for context are often associated with greater visual-spatial detail than false memories (Mather, Henkel, & Johnson, 1997; Norman & Schacter, 1997; Slotnick & Schacter, 2004; Karanian & Slotnick, 2014a, under review), the two views predict different patterns of parahippocampal activity. The visual-spatial processing view predicts that parahippocampal activity will be greater in magnitude during true memories for context than false memories for context because true memories are associated with greater visual-spatial processing than false memories. Alternatively, the general contextual processing view predicts that the magnitudes of parahippocampal activity will be similar during true memories for context and false memories for context because both types of memories are associated with similar degrees of contextual processing. We also expected to find that confident true memories and confident false memories for context would be associated with activity in other context processing regions including the hippocampus, the retrosplenial cortex, and the medial prefrontal cortex (e.g., Bar, Aminoff, & Schacter, 2008; Ranganath, 2010; Slotnick, 2010b; Aminoff, Kveraga, & Bar, 2013; Rugg & Vilberg, 2013). To anticipate the results, we found that true memories for context and false memories for context activated the parahippocampal cortex to a similar degree, which provides support for the general contextual processing view.

Methods

Participants

Sixteen students from Boston College (12 females, age range 20-29 years old) participated in the study. Participants were right-handed, native English speakers, and had normal or corrected-to-normal vision. The Boston College Institutional Review Board approved the protocols. Informed and written consent was obtained before each session. Participants were compensated $10 for the behavioral training session and $25/hour for the fMRI session.

Stimuli and procedure

During fMRI, participants completed either 7 or 8 memory runs. Fourteen participants completed 8 memory runs, one participant completed 7 runs due to timing limitations, and one participant completed 7 runs due to a stimulus presentation programming error. For each run, during the encoding phase, 32 colored abstract shapes spanning 6.7° of visual angle were presented in the left or right visual field with the nearest edge 3.6° of visual angle from fixation (Figure 1A; for shape construction details, see Slotnick & Schacter, 2004). Each shape was presented for 2.5 s followed by a 0.5 s fixation period. Shape sets were randomized and presented sequentially two times (each shape was presented at only one spatial location). Participants were instructed to remember each shape and its spatial location. Immediately after the encoding phase and before the retrieval phase, an instruction screen was displayed for 8.0 s followed by a 2.0 s fixation period. During the retrieval phase of each run, shapes from encoding were randomized and presented sequentially at fixation (Figure 1B). New shapes were not presented during the retrieval phase. Each shape spanned 6.7° of visual angle and was presented for 3.0 s (Figure 1). Immediately after each shape, a confidence rating (U S V) screen was presented for 2.5 s followed by a fixation period of 0.5 to 4.5 s. This resulted in an inter-trial-interval of 6.0 to 10.0 s, which is sufficient to allow for the deconvolution of the hemodynamic response. Participants classified each shape as previously in the "left" or "right" visual field and then made a confidence response (*"unsure"*, *"sure"*, *"very sure"*). If the participant did not make a spatial location response while the stimulus was presented and a confidence rating response while the confidence rating screen was presented, this was classified as a no-response trial. During both encoding and retrieval, no more than three items of a given type (i.e., left spatial location or right spatial location) were sequentially presented and participants were instructed to maintain fixation. Shapes were never repeated across runs. The spatial location of each shape (left, right) was counterbalanced across participants using a Latin Square design.

Confident true memories for context were defined as a correct spatial context response with a high or medium confidence rating (*left-"left"-"very sure", right-"right"-"very sure", left-"left"-"sure",* or *right-"right"-"sure"*), while low confidence true memories for context were defined as a correct spatial context response with a low confidence rating (*left-"left"-"unsure"* or *right-"right"-"unsure"*). Confident false memories for context were defined as an incorrect spatial context response with a high or medium confidence rating (*left-"right"-"very sure", right-"left"-"very sure", left-"right"-"sure",* or *right-"left"-"sure"*), while low confidence false memories for context were defined as an incorrect spatial context response with a low confidence rating (*left-"right"-"unsure"* or *right-"left"-"unsure"*).

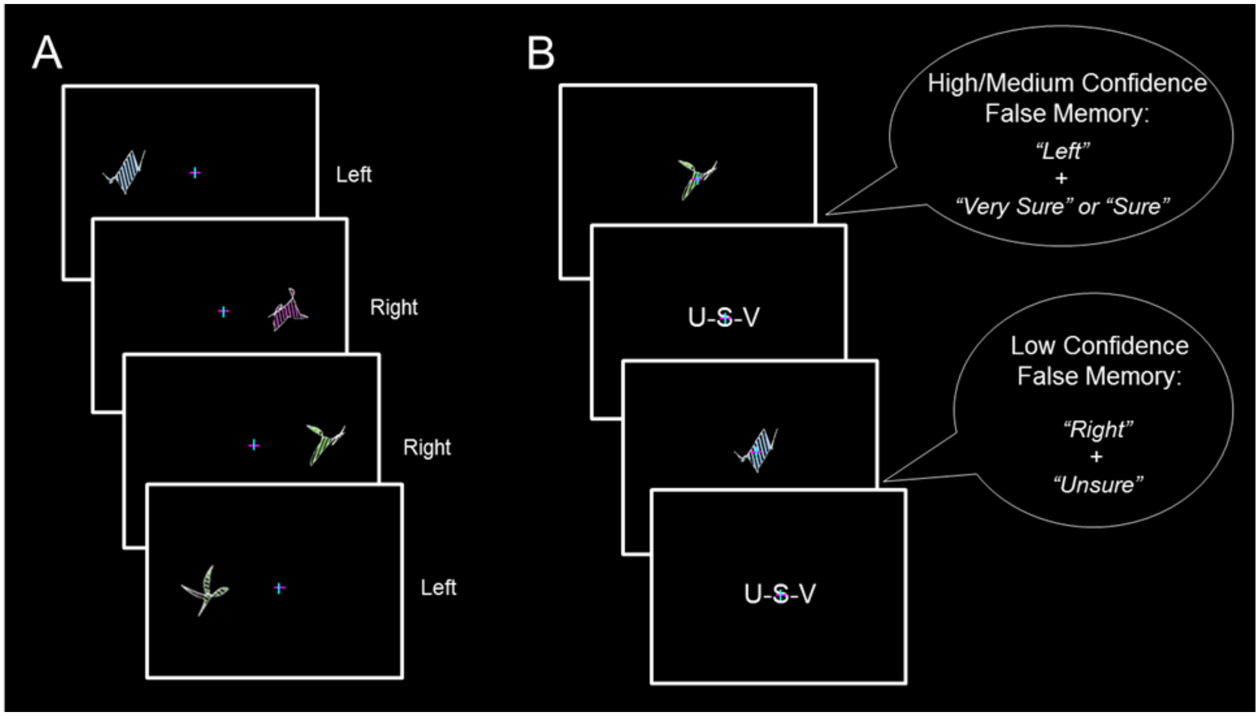


Figure 1. Context memory paradigm. A, During encoding, shapes were presented in the left visual field or the right visual field (item types are shown to the right). B, During retrieval, shapes were presented in the center of the screen and participants identified each as previously in the "left" or "right" visual field, followed by an "unsure"-"sure"-"very sure" confidence rating (illustrative responses are displayed to the right).

Data acquisition and analysis

Data were acquired using a Siemens 3 Tesla Trio Scanner (Erlangen, Germany) with a 32-channel head coil. Functional images were acquired with an echo planar imaging sequence (TR = 2000 ms, TE = 30 ms, flip angle = 90°, field-of-view = 256 × 256 mm, acquisition matrix = 64 × 64, slices = 33, slice acquisition order = interleaved bottom-to-top, slice thickness = 4 mm, no gap; 4 mm isotropic resolution). Anatomic images were acquired with a magnetized prepared rapid gradient echo sequence (TR = 30 ms, TE = 3.3 ms, flip angle = 40°, field-of-view = 256 × 256 mm, acquisition matrix = 256 × 256, slices = 128, slice thickness = 1 mm; 1.33 × 1 × 1 mm resolution). Analyses were conducted with Brain Voyager QX (Brain Innovation B.V., Maastrict, The Netherlands). Pre-processing included slice-time correction, motion correction, and temporal filtering by removal of linear trends and components at or below 2 cycles per run length (using a general linear model to remove low frequency Fourier basis sets). Voxels were resampled at 3 x 3 x 3 mm. To maximize spatial resolution, spatial smoothing was not conducted. Anatomic and functional images were transformed into Talairach space.

A random-effect general linear model was conducted. The protocol of each event (i.e., a square wave defined by each event onset and the subsequent behavioral response) was convolved with a canonical hemodynamic response function to produce each hemodynamic response model for every participant. Both encoding trials and no-response trials during retrieval (i.e., trials in which no response was provided) were assumed to have durations of 2.5 s. The mean level of activity for each run was also modeled with a constant.

A whole-brain analysis was conducted. Only activations in our regions of interest were considered: the parahippocampal cortex, the hippocampus, the retrosplenial cortex, the medial prefrontal cortex, and visual processing regions. These regions were selected based on prior evidence that they play an important role in memory for visual associative/contextual information (e.g., Bar, Aminoff, & Schacter, 2008; Ranganath, 2010; Slotnick, 2010b; Aminoff, Kveraga, & Bar, 2013; Rugg & Vilberg, 2013). Other areas of activation are available upon request from J.M.K. Medial temporal lobe regions were localized on the group average anatomic volume based on known anatomical distinctions (Pruessner et al., 2002; Bernasconi et al., 2003). An individual voxel threshold of $p < .001$ was enforced for all contrasts, whole-brain false discovery rate corrected for multiple comparisons to $p < .05$. False discovery rate correction for multiple comparisons ensures an acceptable rate of false positives across the entire brain for a given individual voxel threshold; thus, it does not require a minimal cluster extent (Logan & Rowe, 2004). All contrasts were weighted to account for differences in the number of each trial type. Activity within the medial temporal lobe was displayed on coronal slices. Activity in the other cortical regions was projected onto a sagittal slice or a representative inflated cortical surface (see Slotnick, 2005). Only data from retrieval were presented.

Event-related activation timecourses were extracted from each activation of interest within the time range of –2 to 12 s after stimulus onset (baseline corrected from –2 to 0 s). To avoid violation of independence, statistical analyses were based on average activity from 6 to 8 s after stimulus onset, the expected maximum of the hemodynamic response (Karanian & Slotnick, 2014a; Slotnick & Schacter, 2004).

Results

Behavioral Results

Memory accuracy (i.e., percentage of hits, collapsed over confidence; chance = 50%) was at an intermediate level (77.03% ± 1.19%; Mean ± 1 SE). As performance did not differ between shapes previously presented in the left visual field (75.50% correct) and shapes previously presented in the right visual field (78.60% correct; *t* (15) < 1), we collapsed over spatial location in the present analysis. The analysis included 193.69 ± 3.45 true memory trials and 57.69 ± 2.88 false memory trials per participant (Mean ± 1 SE). Table 1 shows the average percentage of responses for true memory and false memory as a function of confidence.

True memory and false memory activity in the parahippocampal cortex

We assessed whether high/medium confidence true memories for context and high/medium confidence false memories for context were mediated by similar regions of the parahippocampal cortex. Accordingly, we conducted the conjunction of high/medium confidence true memories for context and high/medium confidence false memories for context (i.e., (*high/medium confidence true memories > low confidence true memories) ∩ (high/medium confidence false memories > low confidence false memories)*). This conjunction produced activity in the parahippocampal cortex (Figure 2A).

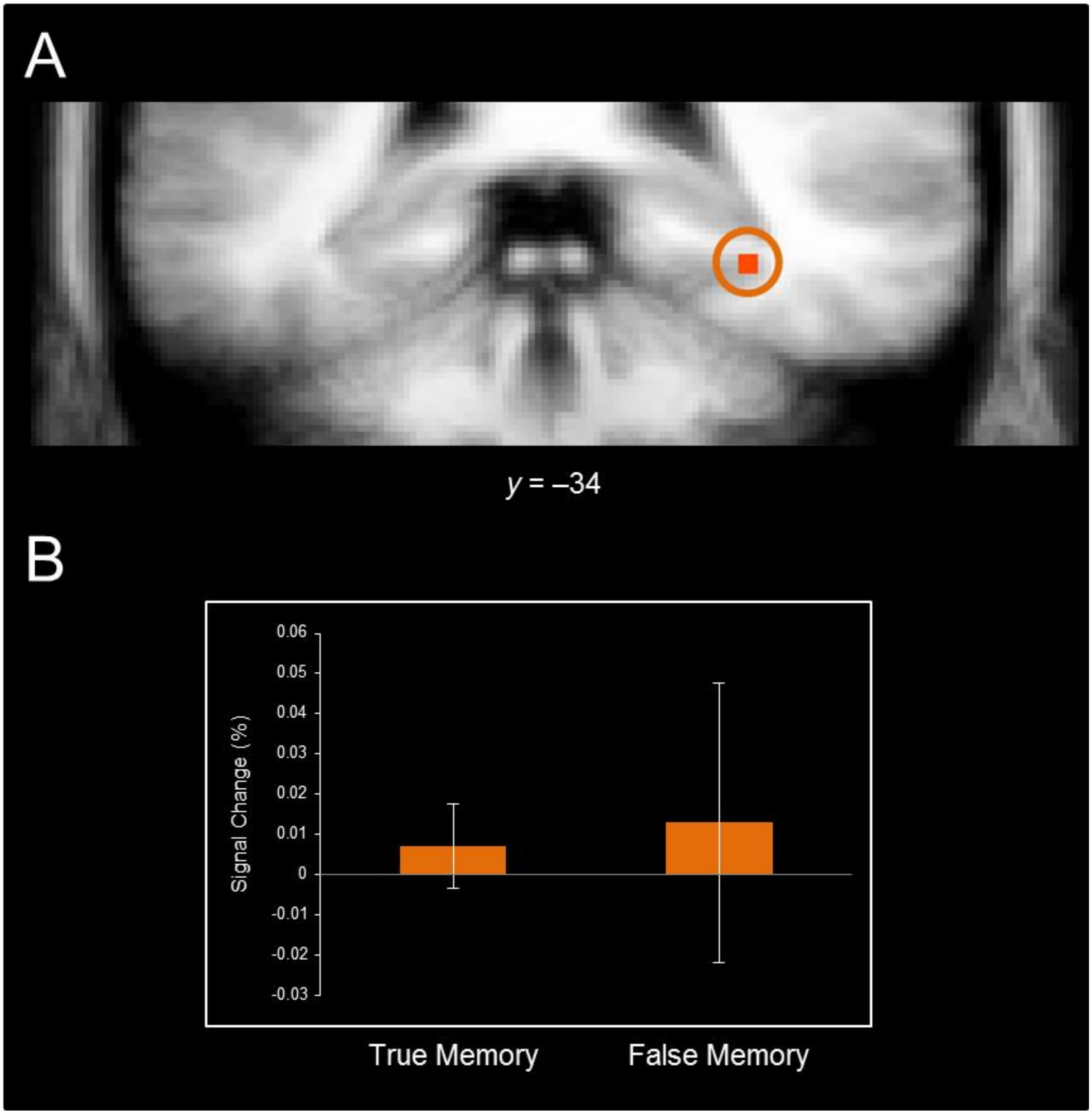
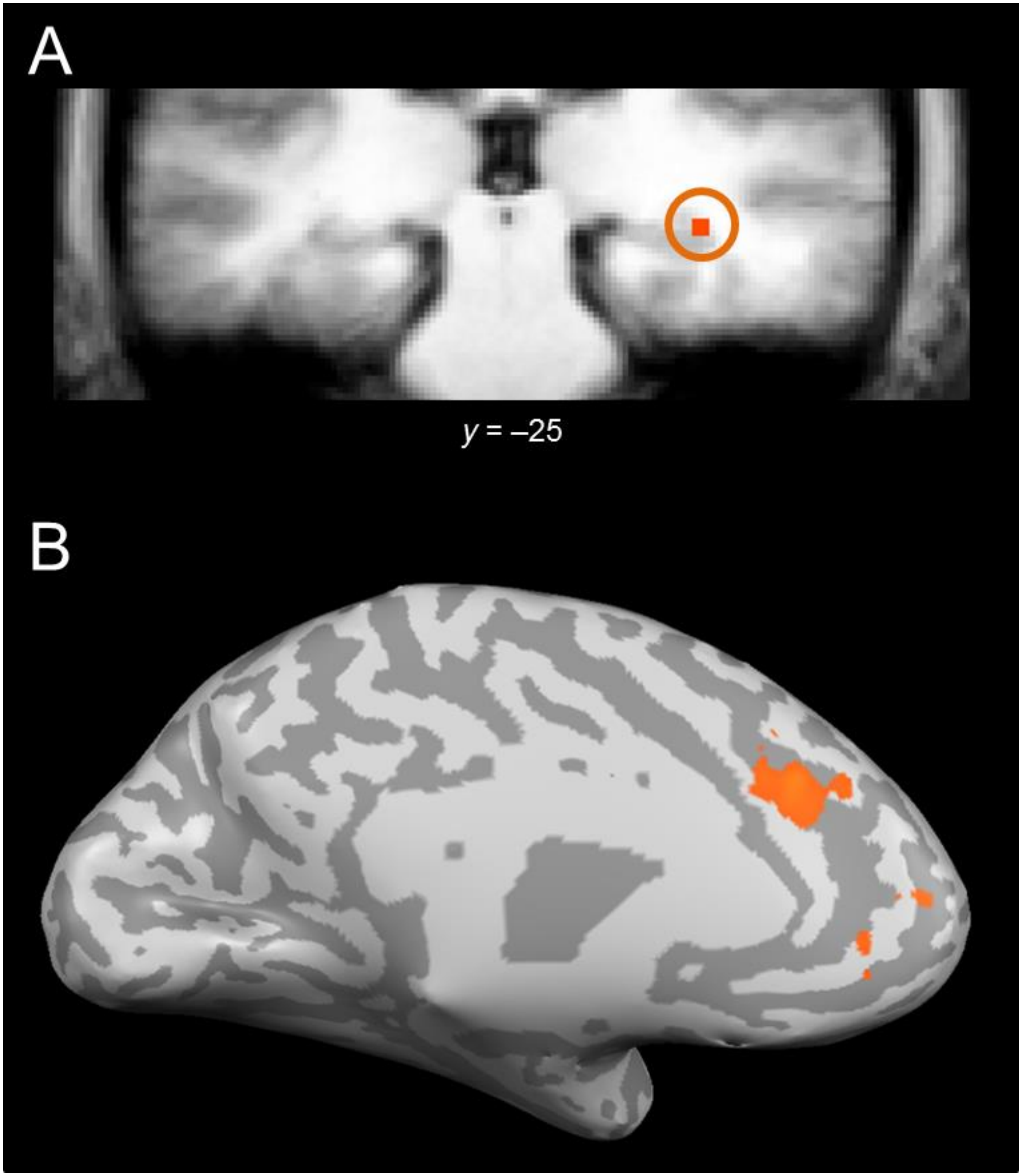


Figure. 2. High/medium confidence true memory ∩ high/medium confidence false memory activity in the parahippocampal cortex. A, Activity in the parahippocampal cortex (coronal view; activation is circled). B, True memory and false memory activity extracted from the parahippocampal cortex activation circled above.

Other context processing areas were also identified by this conjunction, including the hippocampus (Supplemental Figure 1A) and the medial prefrontal cortex (Supplemental Figure 1B). All activations within our regions of interest are listed in Table 2.

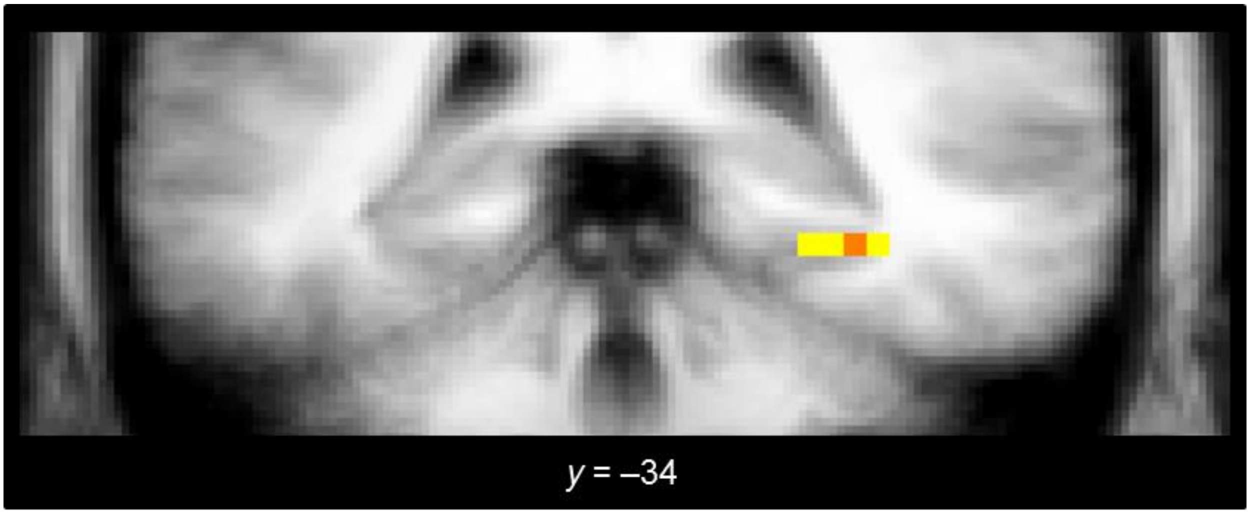


Supplemental Figure 1. High/medium confidence true memory ∩ high/medium confidence false memory activity in other context processing regions. A, Activity in the hippocampus (coronal view; activation circled). B, Activity in the medial prefrontal cortex (medial view).

To distinguish between the visual-spatial processing view and the general contextual processing view, we extracted activity from the parahippocampal cortex activation identified by the above conjunction (i.e., (*high/medium confidence true memories* > *low confidence true memories)* ∩ *(high/medium confidence false memories* > *low confidence false memories)*). We then conducted an analysis of variance to evaluate the magnitudes of true memory and false memory activity in the parahippocampal cortex. As mentioned in the introduction, the visual-spatial processing view predicts that true memories will produce a greater magnitude of activity in the parahippocampal cortex than false memories (i.e., there will be a main effect of accuracy), whereas the general contextual processing view predicts that the magnitude of activity in the parahippocampal cortex will not differ between true memories and false memories (i.e., there will not be a main effect of memory accuracy). The interaction of memory accuracy (true memory, false memory) and confidence (high/medium, low) was not significant (F (1, 15) < 1), and there was no significant main effect of memory accuracy (true memory, false memory) in the parahippocampal cortex (F (1, 15) < 1). Specifically, the magnitude of parahippocampal activity for true memories for context was 0.007 ± 0.011 and the magnitude of activity for false memories for context was 0.014 ± 0.035 (Figure 2B).

It is possible that other regions of the parahippocampal cortex may have been preferentially associated with true memories for context as compared to false memories for context. To assess this possibility, we contrasted true memories for context and false memories for context (i.e., *high/medium/low confidence true memories* > *high/medium/low confidence false memories*), which did not reveal any significant activity in the parahippocampal cortex. The reverse contrast (i.e., *high/medium/low confidence false memories* > *high/medium/low confidence true memories*) also produced null results in this region. Together, these contrasts suggest that true memories for context and false memories for context activated the parahippocampal cortex to a similar degree during retrieval.

We also assessed the extent of activity in the parahippocampal cortex that was associated with high/medium confidence true memories (i.e., *high/medium confidence* > *low confidence true memories*) and high/medium confidence false memories (i.e., *high/medium* *confidence > low confidence false memories*). In addition to the overlapping activity revealed by the conjunction of high/medium confidence true memories and high/medium confidence false memories, high/medium confidence true memories activated distinct regions of the parahippocampal cortex (Supplemental Figure 2). It should be noted that the extent of activity associated with true memories was greater than the extent of activity associated with false memories.



Supplemental Figure 2. True memory activity and false memory activity in the parahippocampal cortex. Activity associated with high/medium confidence true memory (in yellow). Activity associated with both high/medium confidence true memory and high/medium confidence false memory (in orange).

True memory and false memory activity in visual cortical regions

The previous interpretations were based on the assumption that true memories for context were associated with greater visual-spatial detail than false memories for context in the present paradigm, which has been observed in many previous studies (Mather, Henkel, & Johnson, 1997; Norman & Schacter, 1997; Slotnick & Schacter, 2004; Karanian & Slotnick, 2014a, under review). However, proponents of the visual-spatial processing view could argue that the similar magnitudes of parahippocampal cortex activity for true memories and false memories resulted from similar degrees of visual-spatial detail in the current paradigm. To test this possibility, we assessed whether the conjunction of high/medium confidence true memories and high/medium confidence false memories produced activity in visual processing regions. This conjunction produced significant activity in right visual processing regions (Figure 3A). We then extracted true memory activity and false memory activity from the most posterior activation (Figure 3B). Analysis of this activity revealed a main effect of memory accuracy (after collapsing across confidence): the magnitude of activity associated with true memory (0.055 ± 0.014) was significantly greater than the magnitude of activity associated with false memory (0.006 ± 0.020; F (1, 15) = 3.80, $p < 0.05$, one-tailed). Activity associated with true memory was significantly greater than baseline (t (15) = 3.82, $p < .005$), while activity associated with false memory did not significantly differ from baseline (t (15) < 1). Furthermore, both activity associated with high/medium confidence true memory (t (15) = 2.55, $p < .05$) and low confidence true memory (t (15) = 2.88, $p < .01$) were significantly greater than baseline, while neither high/medium confidence false memory nor low confidence false memory differed significantly from baseline (both ts (15) < 1.57, ps > .14). These results indicate that there was greater visual-spatial processing during true memories than false memories.

We also determined whether there were differences in visual processing regions using a direct contrast (i.e., *high/medium/low confidence true memories* > *high/medium/low confidence false memories*). The contrast of true memories for context and false memories for context produced significantly greater activity in V1 and extrastriate cortical regions (Supplemental Figure 3). The reverse contrast (i.e., *high/medium/low confidence false memories* > *high/medium/low confidence true memories*) did not reveal any significant activity in visual processing regions. These findings provide additional evidence that true memories for context produced greater activity in visual processing regions than false memories for context and indicate that true memories were associated with a greater degree of visual-spatial processing in the present paradigm.

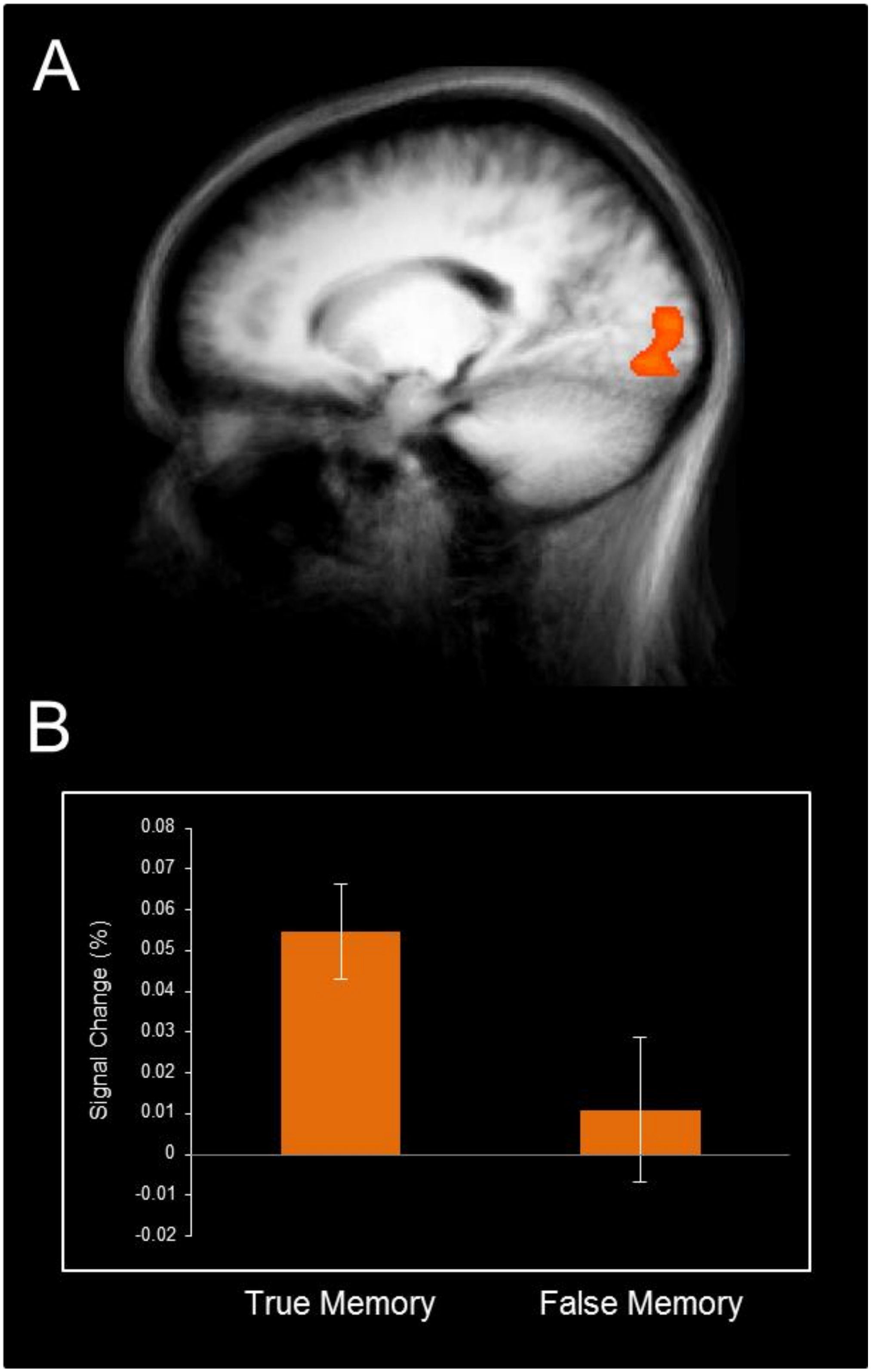
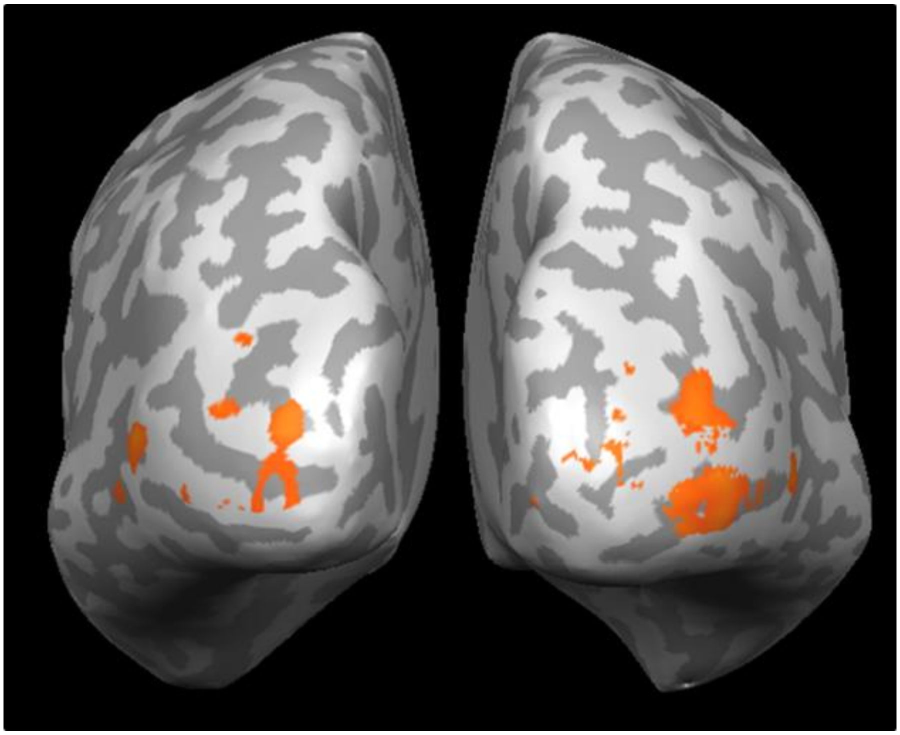


Figure 3. High/medium confidence true memory ∩ high/medium confidence false memory activity in visual processing regions. A, Activity in visual processing regions (sagittal view of right hemisphere). B, True memory and false memory activity extracted from the activation shown above.



Supplemental Figure 3. True memory > false memory activity in visual processing regions (posterior view).

Parahippocampal cortex and visual cortex comparisons

The patterns of activity in the parahippocampal cortex (see Figure 2B) and the visual cortex (see Figure 3B) suggest that each region has a unique functional role during retrieval. Thus, we also evaluated the magnitude of true memory and false memory activity in these regions. The magnitude of true memory activity in the visual processing region was significantly greater than the magnitude of activity in the parahippocampal cortex (t (15) = 2.68, $p < .01$), while the magnitude of false memory activity did not significantly differ between these regions (t (15) < 1).

Discussion

The comparison between the magnitude of true memory activity and false memory activity in the parahippocampal cortex is of particular relevance to the debate regarding the functional role of the parahippocampal cortex. Under the assumption that true memories are often associated with greater visual-spatial detail than false memories (Mather, Henkel, & Johnson, 1997; Norman & Schacter, 1997; Slotnick & Schacter, 2004; Karanian & Slotnick, 2014a, under review), the visual-spatial processing view predicts that true memories for context would produce a greater magnitude of parahippocampal activity than false memories for context. The general contextual processing view predicts that true memories for context and false memories for context would produce similar magnitudes of parahippocampal cortex activity. The conjunction analysis revealed that true memories for context and false memories for context produced similar magnitudes of parahippocampal cortex activity, which indicates that the parahippocampal cortex is not sensitive to differences in visual-spatial detail. The analogous analysis in visual regions produced differential activity for true memories for context and false memories for context. The present results indicate that the parahippocampal cortex is not sensitive to visual-spatial information and is rather sensitive to contextual processing during retrieval. This pattern of results directly contradicts the visual-spatial processing view.

The conjunction of confident true memories and confident false memories (i.e., (*high/medium confidence true memories > low confidence true memories) ∩ (high/medium confidence false memories > low confidence false memories)* produced activity in the parahippocampal cortex. This finding is consistent with previous results indicating that the parahippocampal cortex tracks the strength of subjective contextual processing (i.e., there is greater activity in this region during high confidence contextual processing than low confidence contextual processing). Specifically, in true memory studies (e.g., Kirwan & Stark, 2004; Ranganath et al., 2004; Tendolkar et al, 2008; Slotnick, 2013a; 2013b; Diana, in press), there has been greater parahippocampal cortex activity associated with high confidence memories as compared to low confidence memories. For instance, Tendolkar et al. (2008) demonstrated that retrieval-related activity in the parahippocampal cortex increased linearly based on the amount of context information retrieved. The present findings are also consistent with previous false memory results (Dennis et al., 2012; Karanian 2014b; but see Abe et al., 2013). For example, Dennis et al. (2012) investigated neural differences associated with recollection-based false memory and familiarity-based false memory. These two types of false memory differ in that recollection-based false memory involves the inaccurate retrieval of item and context information, while familiarity-based retrieval only involves inaccurate retrieval of item information. Such recollection-based false memories are similar to high/medium confidence false memories for context in the present study, as recollection has been shown to be highly correlated with high confidence judgements (Tulving, 1985; Rotello et al., 2005; Slotnick, 2010a). Similar to the present results, Dennis et al. (2012) demonstrated that recollection-based false memories were more associated with the parahippocampal cortex than familiarity-based false memories. Another fMRI study provided further evidence that false memories for context can produce activity in the parahippocampal cortex (Gershman, Schapiro, Hupbach, & Norman, 2013). Participants encoded two distinct lists of visual items. Critically, in addition to the items, list 1 also contained scene images. At retrieval, objects from list 1 and list 2 were presented and participants identified the previous context of each item (i.e., list 1 or list 2). Items from list 2 were misattributed to list 1 significantly more often than items from list 1 were misattributed to list 2. Retrieval-related activity in the posterior parahippocampal cortex was evaluated to determine whether reinstatement of the list 1 context (i.e., scene images) was associated with source misattributions for list 2 items. The magnitude of activity in the posterior parahippocampal cortex during retrieval predicted the confidence of these source misattributions. Such evidence is consistent with the present findings in which false memories were associated with activity in the parahippocampal cortex. In addition to the parahippocampal cortex, other cortical context processing regions (i.e., the hippocampus and the medial prefrontal cortex) were identified by the conjunction of high/medium confidence true memories and high/medium confidence false memories (i.e., (*high/medium confidence true memories > low confidence true memories) ∩ (high/medium confidence false memories > low confidence false memories)*). This is consistent with previous findings that these regions are important in contextual processing (e.g., Bar et al., 2008; Ranganath, 2010; Slotnick, 2010b; Aminoff et al., 2013; Rugg & Vilberg, 2013). Together with prior work, the present finding that confident memories for context were associated with activity in the parahippocampal cortex and other context processing regions suggests that the parahippocampal cortex tracks the subjective strength of memories for context. Such evidence provides support for the general contextual processing view.

It is noteworthy that proponents of the visual-spatial processing view have pointed to the inconsistency of results supporting the contextual processing view of the parahippocampal cortex (Epstein & Ward, 2010). That is, a number of studies investigating true memory for context have failed to identify parahippocampal cortex activity when comparing accurate context memory and inaccurate context memory. For instance, within the visual modality, Peters et al. (2007) contrasted accurate and inaccurate context memories, which did not produce significant activity in the parahippocampal cortex. However, upon examination of the timecourses extracted from the parahippocampal cortex, the null results did not appear to be driven by a lack of activity in the parahippocampal cortex during accurate context memories but rather may be attributable to an increase in parahippocampal cortex activity for inaccurate context memories. That is, accurate and inaccurate memories appear to have activated the parahippocampal cortex to a similar degree. In the paradigm employed by Peters et al., (2007), inaccurate context memories were similar to false memories for context, as incorrect context memories were defined as attributing an old item to the wrong context (i.e., auditory context vs. visual context; cf., Karanian & Slotnick, 2014b). Such evidence indicates that true memories for context and false memories for context can activate the parahippocampal cortex to a similar degree, which may explain some of the null findings within the parahippocampal cortex literature. This is a topic for future research.

There is some fMRI evidence that suggests the parahippocampal cortex varies in function along the anterior-posterior axis. The anterior parahippocampal cortex has been preferentially associated with retrieval of contextual information (e.g., Ekstrom & Bookheimer, 2007; Epstein, 2008; Xu, Evensmoen, Lehn, Pintzka, & Haberg, 2010), while the posterior parahippocampal cortex has been preferentially associated with perception of contextual information (e.g., Epstein & Kanwisher, 1998; Epstein et al., 1999; Epstein, 2008). In the present study, our analyses identified retrieval-related activity within the posterior parahippocampal cortex. Thus, our findings are in line with the view that perception- and memory-related contextual processing can be mediated by both anterior and posterior aspects of the parahippocampal cortex (Aminoff, Gronau, & Bar, 2007).

The behavioral literature has also investigated the mechanism that supports the construction of highly confident false memories in old-new recognition/Deese-Roediger-McDermott (DRM) paradigms in which participants falsely remember related lures as old (Roediger & McDermott, 1995). One theory that has emerged to explain such high confidence false memories is content borrowing (Lampinen, Meier, Arnal, & Leding, 2005; Lampinen, Ryals, & Smith, 2008). Lampinen et al. (2005; 2008) have demonstrated that as many as half of vivid false memories produced in DRM paradigms can be attributed to content borrowing, such that details associated with old items were misattributed to lures during retrieval. Content borrowing may help to explain the occurrence of some instances of false memory in the present study. Specifically, the conjunction of confident true memories and confident false memories (i.e., (*high/medium confidence true memories* > *low confidence true memories) ∩ (high/medium confidence false memories* > *low confidence false memories)*) produced activity in visual processing regions, which suggests that content borrowing may have occurred during confident false memories. For instance, it is possible that a shape previously presented in the right visual field was similar to a shape that was previously presented in the left visual field, and such similarity may have induced reinstatement of the incorrect context during retrieval. If this were generally the case for false memories in the present study, similar reinstatement patterns would have been observed in visual processing regions for confident true memories and confident false memories. However, we also found that true memories produced greater activity in visual processing regions than false memories. Nonetheless, it remains possible that content borrowing may explain some of the confident false memories observed in the present study. This is a topic of future research.

In the present study, we found that true memories for context and false memories for context similarly activated the parahippocampal cortex. Furthermore, we found that true memories for context activated visual processing regions to a greater degree than false memories for context. This evidence supports the view that the parahippocampal cortex mediates general processing of contextual information rather than specific visual-spatial processing. Future studies should implement paradigms in which the context is devoid of visual-spatial processing, such as nonspatial (e.g., color) or nonvisual (e.g., auditory) contexts. It is predicted that such studies will provide additional support for the view that the parahippocampal cortex is associated with general contextual processing rather than visual-spatial processing.

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Tables

Table 1. *Behavioral Results.* Percentage of each type of confidence response for true memory and false memory (mean ± SE).

	"Unsure""	***"Sure"***	***"Very Sure"***
True Memory	22.56 ± 1.33	33.38 ± 1.33	44.07 ± 1.70
False Memory	58.04 ± 2.78	33.94 ± 2.25	8.02 ± 1.05

Table 2. fMRI Results. *High/Medium Confidence True Memory* ∩ *High/Medium Confidence False Memory* Activations in Regions of Interest.

Region	***x***	***y***	***z***	***Size (mm^3)***	***Average t***	***Max. t***
Medial Prefrontal Cortex	−14	31	26	2,214	3.25	3.59
Medial Prefrontal Cortex	−21	43	6	3,699	3.42	4.69
Medial Prefrontal Cortex	−18	43	3	189	2.48	2.86
Hippocampus	33	−25	−5	27	2.34	2.34
Parahippocampal Cortex	30	−34	−8	27	2.33	2.33
Visual Cortex	19	−84	0	3,591	2.84	5.59

Talairach coordinates (x, y, z) refer to the center of each activation. t refers to t-value.

GENERAL DISCUSSION

The role of visual cortical regions during true memory for visual features

A number of studies have previously demonstrated that sensory-specific activity is reinstated during memory. For instance, memory for visual information reinstates activity in visual processing regions, while memory for auditory information reinstates activity in auditory processing regions. Such evidence provided a solid foundation for the constructive memory framework. More recent research has probed the specificity of such sensory reinstatement. For instance, within the visual modality, memory for visual features has been associated with sensory reinstatement in feature-specific sensory processing regions, including the color processing region (V8) and retinotopic visual regions (Slotnick 2009a, 2009b). In the present dissertation, I expand this body of work. In Chapter 1, we demonstrated that activity in the motion processing region (MT+) was reactivated when remembering moving shapes, as compared to stationary shapes. Furthermore, in Chapter 2.1, we demonstrated that activity in the shape processing region (LOC) was reactivated when remembering intact shapes, as compared to scrambled shapes. Together, this body of work provides strong evidence that true memory is, in part, underpinned by sensory reinstatement in feature-specific visual processing regions.

The role of visual cortical regions during false memory for visual features

In an fMRI study on the neural correlates of true memory and false memory for visual information, Slotnick and Schacter (2004) reported a sensory signature that distinguished true memories from false memories in early visual regions. Specifically, true memory activity was greater than false memory activity in Brodmann Area (BA) 17 and BA18, while true memory and false memory activity were similar in magnitude in later visual regions (i.e., BA19, BA37). Since 2004, numerous false memory studies have reported results that were consistent with the sensory signature hypothesis (e.g., Dennis, Bowman, & Vanderkar, 2012; Dennis, Johnson, & Petersen, 2014; Gutchess & Schacter, 2012; Kim & Cabeza, 2007; Okado & Stark, 2003; Stark, Okado, & Loftus, 2010). Thus, the sensory signature hypothesis evolved into the current view of the field. Specifically, the dominant view in the field posits that (1) true memories for visual information activate early visual cortical regions to a greater degree than false memories, and (2) false memories for visual information are not driven by activity in early visual cortical regions but are instead associated with activity in later visual cortical regions as well as more anterior, conscious processing regions.

It has been proposed that true memory activity in early visual cortical regions (e.g., V1, MT+) reflects implicit memory processes, and likely results from nonconscious sensory reinstatement (e.g., Crick & Koch, 1995; Slotnick & Schacter, 2004; Tong, 2003). Specifically, this view posits that encoding-related activity is rapidly and nonconsciously reinstated in early visual regions upon the presentation of a previously seen item during the retrieval phase. The reinstatement of encoding-related activity cannot occur for false memories, as the item falsely endorsed as old was never encoded. As stated above, the dominant view in the field predicts greater true memory than false memory activity in early visual regions. In Chapters 1 and 2, we provide evidence that supports this view. Specifically, in Chapter 1, we demonstrated that true memory for motion activated the motion processing cortex to a greater degree than false memory for motion. Furthermore, in Chapter 2.2, we demonstrated that true memory for shape activated the shape processing cortex to a greater degree than false memory for shape. As previously posited, it is likely that such differential activity for true memory and false memory resulted from nonconscious sensory reinstatement.

The second component of the dominant view further posits that false memories do not activate early visual regions, as these regions support nonconscious/implicit memory processes. Instead, this view posits that false memories are associated with regions that support conscious memory processes, such as later visual regions and more anterior, conscious processing regions (e.g., the dorsolateral prefrontal cortex). The idea that false memories are associated with activity in conscious processing regions has been well-supported by fMRI evidence (for a meta-analysis, see Kurkela & Dennis, 2016). In the present study, we employed false memory paradigms in which participants were asked to recall specific item features (i.e., whether an item was previously moving or stationary, or whether a shape was previously intact or scrambled), and we predicted that such detailed false memory may be associated with activity in feature-specific visual processing regions. However, in Chapter 1, we demonstrated that false memory for motion was not associated with activity in the motion processing cortex, which is consistent with the current view.

In Chapter 2, we posited that the motion processing cortex, a region associated with largely nonconscious processing, may not be representative of other early visual cortical regions. Specifically, we hypothesized that early visual regions that are involved in largely conscious processing – such as shape processing cortex – may function differently during false memory construction. In Chapter 2.2, we demonstrated that false memory for shape activated the shape processing cortex, which challenges the view that false memories do not produce activity in early sensory regions. We posited that this differential pattern of true memory and false memory activity reflects relatively nonconscious and conscious processing within MT+ and LOC, respectively. That is, we proposed that the differential pattern of activity likely stems from the distinct functional processing that occurs within these regions of early sensory cortex (Figure 1). Such evidence directly challenges the view that false memory is underpinned by higher-level conscious processing regions. Instead, the present evidence suggests that whether or not sensory regions will be involved in false memory construction may be dependent on the contents of the memory. Understanding the precise manner in which such regions of the sensory cortex contribute to the construction of false memories remains a topic for future research.

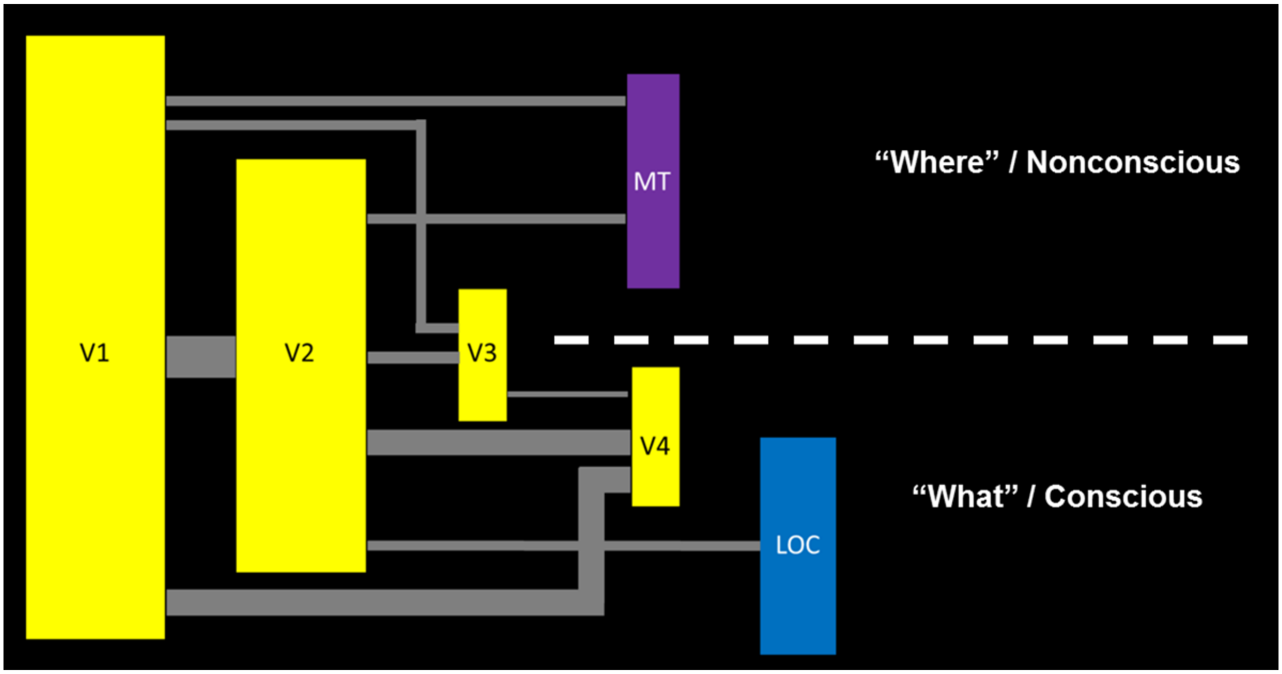

Figure 1. Anatomical differences across the motion processing cortex (MT, in purple) and shape processing cortex (LOC, in blue).Top, the "where" pathway, which reflects nonconscious processing. Bottom, the "what" pathway, which largely reflects conscious processing (Figure adapted from Felleman & Van Essen, 1991).

The role of the parahippocampal cortex during false memory

A large number of studies within the field of perception have demonstrated that the parahippocampal cortex has been associated with visual-spatial processing, and such evidence has contributed to the view that the primary function of the parahippocampal cortex is to only process visual-spatial information (i.e., the visual-spatial processing view; Epstein & Ward, 2010). However, within the field of memory, there is evidence that the parahippocampal cortex plays a broader role than visual-spatial processing. That is, the memory literature suggests that the parahippocampal cortex processes both visual-spatial and non-spatial information. Such evidence has given rise to the general context processing view of the parahippocampal cortex (Aminoff et al. 2013).

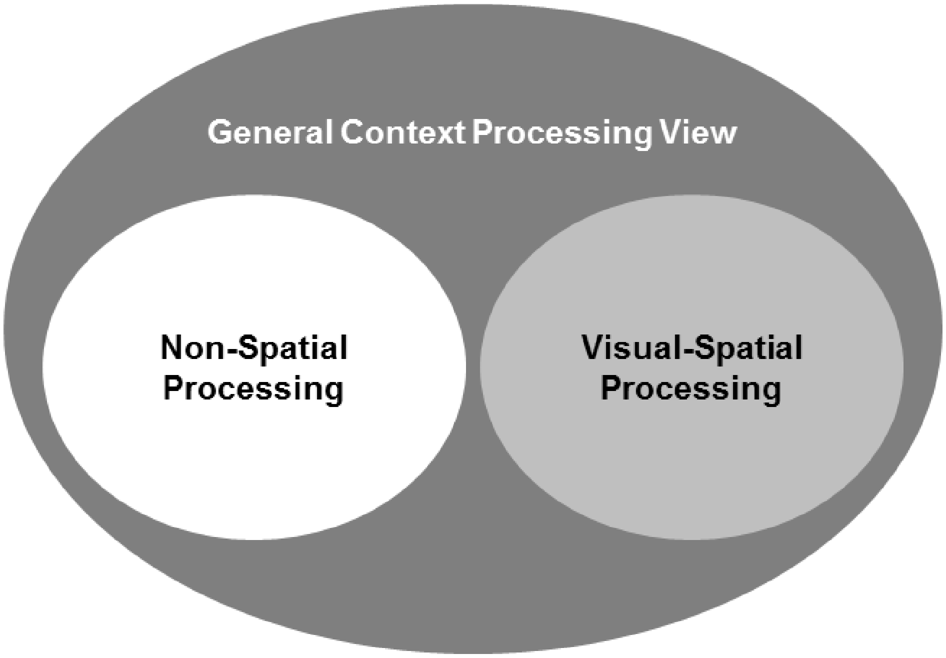

Figure 2. The general contextual processing view, as compared to the visual-spatial processing view of the parahippocampal cortex.

In Chapter 3, we employed two paradigms in which we assessed these competing hypotheses via the comparison of activity associated with true memory and false memory. Critically, under the assumption that true memories for context are often associated with greater visual-spatial detail than false memories, the two views predict different patterns of parahippocampal activity. The visual-spatial processing view predicts that parahippocampal activity will be greater in magnitude for true memory than false memory, while the general context processing view predicts that the magnitudes of parahippocampal activity will be similar for true memory and false memory.

In Chapter 3.1, we employed a paradigm in which items were presented as either moving or stationary during encoding. During retrieval, old items were presented and participants identified the previous context of each item as previously “moving” or “stationary”. False memories for the context of motion (i.e., “moving”/stationary) produced activity in the parahippocampal cortex. The evidence from this study suggests that false memory for context, like true memory for context, can activate the parahippocampal cortex. While such evidence supports the general context processing view, it is not immune from the visual-spatial processing account. That is, it is conceivable that retrieval of the motion context induced more visual-spatial processing than retrieval of the stationary context.

In Chapter 3.2, to better assess the functional role of the parahippocampal cortex, we employed an fMRI source memory paradigm in which shapes were either presented to the left of fixation (i.e., the left spatial context) or to the right of fixation (i.e., the right spatial context). During retrieval, we assessed the relative magnitude of activity in the parahippocampal cortex during true memory and false memory. In support of the general context processing view, we found that true memory for context and false memory for context activated the parahippocampal cortex to a similar degree. Together, these studies provide support for the general context processing view, as opposed to the visual-spatial processing view.

General Conclusions

The studies presented within this dissertation investigated the neural underpinnings of true memory and false memory for visual information. Specifically, the studies presented in Chapter 1 and Chapter 2 investigated the role of sensory cortical regions, including the motion processing region and the shape processing region, in the construction of true memory and false memory for visual features. The studies presented in Chapter 3 investigated the role of the parahippocampal cortex –a control region within the medial temporal lobe–during false memory construction. In addition, the results from Chapter 3 inform a broader debate on the functional role of the parahippocampal cortex. Together, the studies presented in this dissertation highlight both similar and distinct roles of sensory processing and control regions in both true memory and false memory construction.

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