



## Research report

# The retrieval of perceptual memory details depends on right hippocampal integrity and activation



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## ABSTRACT

We assessed whether perceptual richness, a defining feature of episodic memory, depends on the engagement and integrity of the hippocampus during episodic memory retrieval. We tested participants' memory for complex laboratory events (LEs) that differed in perceptual content: short stories were either presented as perceptually rich film clips or as perceptually impoverished narratives. Participants underwent functional magnetic resonance imaging (fMRI) while retrieving these LEs (narratives and clips), as well as events from their personal life (autobiographical memories). In a group of healthy adults, a conjunction analysis showed that both real-life and laboratory memories engaged overlapping regions from an autobiographical memory (AM) retrieval network, indicating that laboratory memories mimicked autobiographical events successfully. A direct contrast between the film clip and the narrative laboratory conditions identified regions activated by the retrieval of perceptual memory content, which included the right hippocampus, parahippocampal gyrus, middle occipital gyrus and precuneus. In individuals with medial temporal lobe epilepsy (mTLE) originating from the right hippocampus, the magnitude of this "perceptually rich" signal was reduced significantly, which is consistent with evidence of reduced perceptual memory content in this clinical population. In healthy controls, right hippocampal activation also correlated positively with a behavioral measure of perceptual content in the clip condition. Thus, right hippocampal activity contributed to the retrieval of perceptual episodic memory content in the healthy brain, while right hippocampal damage disrupted activation in regions that process perceptual memory content. Our results suggest that the hippocampus contributes to recollection by retrieving and integrating perceptual details into vivid memory constructs.

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## 1. Introduction

It is well established that the human hippocampus plays an essential role in recollection, the sense of traveling mentally back in time to relive past events (e.g., [Moscovitch & McAndrews, 2002](#); [Moscovitch et al., 2005](#); [Nadel & Moscovitch, 1997](#); [Piolino, Desgranges, & Eustache, 2009](#); [Ranganath, 2010](#); [Rugg & Vilberg, 2013](#)). The nature of the cognitive processes and neural mechanisms through which hippocampal activity gives rise to an evocative memory experience, however, is under debate. With the current study, we investigated whether hippocampal activation and integrity are essential to the retrieval of rich sensory-based memory details. Our goal was to advance our understanding of hippocampal function by documenting a mechanism bridging hippocampal activation to the phenomenological experience of recollection.

Most current theories of hippocampal function stipulate that this structure is essential for episodic memory to retain its signature context-specific details ([Tulving, 1985, 2002](#)). Multiple Trace Theory ([Moscovitch et al., 2005](#); [Nadel & Moscovitch, 1997](#)) and, more recently, the Transformation Hypothesis of memory consolidation ([Winocur & Moscovitch, 2011](#); [Winocur, Moscovitch, & Bontempi, 2010](#)), both suggest that most memory loses contextual specificity over time, but that memories that retain their specificity and level of detail remain dependent on the hippocampus. According to the Binding of Items and Contexts model ([Diana, Yonelinas, & Ranganath, 2007](#); [Ranganath, 2010](#)), the hippocampus supports memory representations that integrate elements into their context, and memory episodes are an example of such integrated representations. Building on this model, [Yonelinas \(2013\)](#) has suggested that the hippocampus performs *complex high-resolution binding* of the different qualitative aspects of an event, both at encoding and at retrieval. Others have proposed that the hippocampus's main role is to integrate disparate elements into complex spatial scenes ([Hassabis & Maguire, 2007](#); [Hassabis, Kumaran, & Maguire, 2007](#)) or simulations of future events ([Addis, Cheng, & Schacter, 2011](#); [Schacter, Addis, & Buckner, 2007](#)). While these theories consider hippocampal function differently, each of them predicts that the hippocampus is essential to retrieve highly context-specific details that comprise our memories for past episodes.

In this theoretical context, we hypothesized that retrieval of sensory-based episodic memory details, or perceptual details, is particularly likely to depend on the hippocampus. Perceptual richness is a core feature of episodic memory that contributes to how vividly we re-experience past life events ([Brewer, 1986, 1995](#); [Conway, 2009](#); [Rubin, Schrauf, & Greenberg, 2003](#)). During recall, visual elements are combined into “scenes” that form the spatial context in which memories are staged. Moreover, perceptual memory details are highly context-specific: percepts do not easily become generalized or abstract, and therefore they form the core of *high-resolution* content ([Yonelinas, 2013](#)). Although some perceptual elements can become integrated into a storyline (e.g., [Monica Lewinski's blue dress](#)), most of the sights, sounds, smells and other percepts that render memory vivid are

peripheral to an event's main themes. In other words, they are unlikely to become part of a memory's gist which, according to [Winocur and Moscovitch \(Winocur & Moscovitch, 2011; Winocur et al., 2010\)](#), can be retained and accessed without involving the hippocampus. For these reasons, we propose that perceptual memory content is a sensitive marker of recollection, and that it should be an important determinant of hippocampal engagement during memory retrieval.

Although some evidence exists in the literature linking hippocampal function to the retrieval of perceptual memory details, this evidence suffers from important limitations. Perceptual richness emerges from the integration of sensory-based memory details into multidimensional memories. However, the study of rich and complex memories—i.e., autobiographical memory (AM)—offers limited experimental control. For example, emotional content and personal significance are memory characteristics that both correlate with perceptual content ([Daselaar et al., 2008](#); [Levine, Svoboda, Hay, Winocur, & Moscovitch, 2002](#); [Rubin et al., 2003](#)) and that are known to modulate hippocampal activity at recall ([Addis, Moscovitch, Crawley, & McAndrews, 2004](#)). On the other hand, most tasks of episodic memory conducted in the laboratory (e.g., item recognition or source memory tasks) make use of stimuli too elemental to capture perceptual richness because this feature emerges from complexity. As such, perceptual richness is not typically assessed in a well-controlled laboratory setting, although several recent functional magnetic resonance imaging (fMRI) studies using more complex multi-sensory stimuli (e.g., short film clips, [Ben-Yakov, Rubinson, & Dudai, 2014](#); [Furman, Mendelsohn, & Dudai, 2012](#)) have shown reliable coding of other event attributes in the hippocampus ([Bonnici, Chadwick, et al., 2013](#); [Chadwick, Hassabis, Weiskopf, & Maguire, 2010](#); [Rugg et al., 2012](#)). Nevertheless, some evidence from the literature suggests a link between hippocampal function and memory's perceptual richness. When events are recalled or imagined, hippocampal engagement correlates with ratings of vividness ([Gilboa, Winocur, Grady, Hevenor, & Moscovitch, 2004](#); [Rabin, Gilboa, Stuss, Mar, & Rosenbaum, 2010](#); [Sheldon & Levine, 2013](#)), imagery content ([Andrews-Hanna, Reidler, Sepulcre, Poulin, & Buckner, 2010](#); [Viard et al., 2007](#)) and sense of reliving ([St Jacques, Kragel & Rubin, 2011](#); [Viard, Desgranges, Eustache, & Piolino, 2012](#); but see [Daselaar et al., 2008](#)). Damage to the medial temporal lobe (MTL) also leads to a deficit in scene construction ([Hassabis, Kumaran, Vann, & Maguire, 2007](#); [Hassabis & Maguire, 2007, 2009](#)) and to a paucity of perceptual AM features ([St-Laurent, Moscovitch, Jadd, & McAndrews, 2014](#); [St-Laurent, Moscovitch, Levine, & McAndrews, 2009](#)).

With the current study, we performed a direct test of the relationship between episodic memory's perceptual richness and hippocampal function. We tested healthy controls and individuals with unilateral medial temporal lobe epilepsy (mTLE), a condition that compromises the integrity of the MTL including the hippocampus proper, on a memory task while they underwent fMRI. The task, which was adapted from a behavioral paradigm we introduced ([St-Laurent et al., 2014](#)), was designed to capture the complexity of AM while

manipulating perceptual richness experimentally. Before scanning, short stories were presented to participants in one of two formats: as perceptually enriched audio-visual film clips, or as perceptually impoverished written narratives; stories were then retrieved using title-cues while participants underwent fMRI. We relied on a cued recall paradigm that is commonly used in studies of AM (Addis, Moscovitch, et al., 2004; Addis, Moscovitch, & McAndrews, 2007; Gilboa et al., 2004; Nadel, Campbell, & Ryan, 2007; Viard et al., 2007) in order to maximize the engagement of the canonical AM retrieval network (Cabeza & St Jacques, 2007; Maguire, 2001a; Svoboda, McKinnon, & Levine, 2006).

With the behavioral version of this task, we conducted a thorough analysis of memory content based on verbal free recall and a detail counting procedure. This analysis established that healthy adults recalled significantly more perceptual memory details for film clips than for narratives, while the number of recalled story elements (the “gist” of the story; i.e., What happened? Who did what? How did characters interact? What was the situation?) was well matched between the two conditions (St-Laurent et al., 2014). By design, memory for the clips and narratives was also matched for emotionality, recency, rehearsal and—absence of—personal relevance. Thus, for the current study, we assumed that a direct contrast between brain activity elicited by the retrieval of film clips versus narratives should reveal brain regions that support perceptual episodic memory content, while controlling for confounds typically associated with the retrieval of naturalistic memories. We predicted that clips should elicit greater activation than narratives in the hippocampus as well as in neocortical regions involved in imagery and sensory processing. In the group of healthy participants, we also correlated hippocampal activation with a measure of perceptual memory content—the Linguistic Inquiry and Word Count’s *Perceptual Processes* category (Pennebaker, Chung, Ireland, Gonzales, & Booth, 2007), which was derived from transcripts of post-scan memory descriptions. Previously, we have shown that this word count measure correlates with manual counts of memory details that reflect perceptual content (St-Laurent et al., 2014). We predicted positive correlations between word count and hippocampal activation, especially in the perceptually rich film clip condition.

In individuals with mTLE tested previously on the behavioral version of this paradigm, we observed that perceptual memory content was reduced disproportionately, especially in the perceptually rich film clip condition (St-Laurent et al., 2014). In fact, perceptual memory content was almost as impoverished for film clips as it was for narratives in the mTLE group. Therefore, we hypothesized that the difference in brain activation between the clip and the narrative condition—a reflection of perceptual memory content—should be significantly more pronounced in controls than in individuals with mTLE tested in the current study. Moreover, we predicted that this reduction should be modulated by hippocampal volume, a marker of the epileptogenic MTL’s integrity, within the mTLE group. We must also mention that the current study only tested patients whose mTLE originated from the right hippocampus. As will become clear in the [Results Section](#), brain activity indicative of perceptual memory content was strongly lateralized to the right hemisphere (including the right

anterior hippocampus). This observation suggests that damage to the right MTL should be especially detrimental to the recruitment of regions involved in the retrieval of perceptual memory content, which motivated our focus on individuals with right unilateral mTLE.

In addition to the clip and narrative conditions, the original behavioral task also included a condition in which participants retrieved personal memory episodes (AM condition). Detail counts indicated that, like film clips, AMs were rich in perceptual details in the controls. In individuals with mTLE, AM perceptual details were reduced disproportionately relative to AM story details that reflected the gist of the event (see also St-Laurent et al., 2009), indicating that perceptual memory content is especially sensitive to MTL damage. In the current fMRI paradigm, we also included an AM condition in order to compare brain activation elicited by personal memories and by the two laboratory conditions. We expected significant overlap between the three memory conditions, with some variations that reflected their respective features. As film clips and AMs were both perceptually rich, we expected hippocampal activation not to differ between these two conditions despite clear differences in other dimensions (e.g., recency, emotionality, personal relevance). We also predicted that AMs and clips should both elicit greater hippocampal activation than narrative retrieval. While others have used videos and narratives to assess the neural correlates of different memory properties (Ben-Yakov & Dudai, 2011; Ben-Yakov, Eshel, & Dudai, 2013; Hasson, Furman, Clark, Dudai, & Davachi, 2008; Kurby & Zacks, 2008; Swallow et al., 2011), the current study is, to the best of our knowledge, the first attempt to contrast videos and narratives directly with real-life memories within the same brain imaging paradigm.

In sum, we used fMRI to measure brain activity while healthy controls and individuals with right-lateralized mTLE recalled film clips, narratives and AMs, and performed a counting control task. We predicted that complex laboratory memories should engage significant portions of the AM retrieval network. In controls, we predicted that a direct contrast between perceptually rich film clips or AMs and perceptually impoverished narratives should reveal brain regions involved in the retrieval of perceptual memory content, including the hippocampus proper. In individuals with mTLE, however, we predicted that difference in activation between the clip and narrative conditions—which is indicative of perceptual memory content—should be reduced, consistently with behavioral evidence of their poor memory for perceptual details.

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## 2. Methods

### 2.1. Participants

Fourteen healthy participants (5 male; mean age = 37.7, SD = 9.9; mean years of education = 16.5, SD = 3.3) with no history of head injury, neurological or psychological disorder were tested in accordance with a protocol approved by the Research Ethics Board of the University Health Network. Twelve individuals with unilateral mTLE lateralized to the right hemisphere were also recruited through the Epilepsy

Clinic at the Toronto Western Hospital and tested on our procedure. Participants were either native (controls:  $n = 8$ ; mTLE:  $n = 10$ ) or completely fluent (controls:  $n = 7$ ; mTLE:  $n = 2$ ) English speakers. Twelve of the 14 control participants who were closest in age to the participants with mTLE were selected for direct comparisons between the two groups (equal samples were selected to balance statistical power). Table 1 presents demographic information about the mTLE participants and the group of 12 controls to whom they were compared, as well as neuropsychological test scores for the mTLE group (two pairs of tests, the Warrington Recognition Memory Test for Words and for Faces (Warrington, 1984), and the Rey Auditory Verbal and Rey Visual Design Learning Tests (Spreen & Strauss, 1991; Strauss, Sherman, & Spreen, 2006), reflect memory for verbal and non-verbal material, respectively). The Matrix Reasoning Subscale of the Wechsler Abbreviated Scale of Intelligence was also administered to controls to estimate non-verbal intelligence and compare their scores to those of individuals with mTLE.

All participants with mTLE were experiencing seizures originating in the right hippocampus at the time of testing, and were candidates for a unilateral temporal lobe resection. Only one participant was diagnosed with bilateral seizures based on intracranial recording: approximately 70% of his seizures originated from the right hippocampus while the remaining 30% originated from the left. The mean age of seizure onset was 22.4 years ( $SD = 16.3$  years). Six of 12 participants began having recurrent seizures before reaching majority (at ages 1, 4, 12, 12, 14 and 16, respectively), while the remaining participants started having seizures in adulthood (18 years and older). Although most patients did not keep a precise seizure diary, seizure frequency was described to range from every few months to daily (e.g., for simple partial seizures). Three patients were on monotherapy (Tegretol, Epival, or Trileptal), seven were taking two anticonvulsants (a

variety) and two were on three anticonvulsant medications. Seven participants were diagnosed with right mesial temporal sclerosis (MTS) based on radiological criteria or, for those who were operated subsequent to participation, on pathological analysis of resected tissue. One participant with mTLE had a small posterior temporal cavernoma on the left hemisphere. In all the other participants, no structural brain damage was observed beside MTS.

## 2.2. Procedure

We adapted the paradigm described by St-Laurent et al. (2014) to fMRI. Twenty-one events from the participants' personal life (AMs) were collected over the phone prior to scanning day. Based on a list of suggestions (Supplementary Material, Section S7), participants selected AMs that had taken place over a year ago and had lasted from within minutes to a few hours. Participants and the experimenter (MSL) agreed on a title for each AM to serve as the in-scan retrieval cue. One hour before scanning, AM titles were re-read to the participant to promote retrieval success. Then, participants completed a pre-scan testing session during which they encoded 40 laboratory events (LEs) presented on a Lenovo T500 computer with E-Prime 2.0.8.22 (Psychology Software Tools Inc.). For each participant, events were assigned pseudo-randomly to either the clip or the narrative condition so that 20 LEs were presented as film clips and the remaining 20 were presented as narratives (Supplementary Material, Fig. S1 and Section S8; St-Laurent et al., 2014). A few pairs of clips within the stimulus set featured the same characters, but no more than one clip per pair was ever assigned to the clip condition. Also, one LE was always assigned to the narrative condition because the clip's sound track was corrupted.

Clips were 23 sec in duration and they contained minimal or no English dialog so that the story was carried by the actions of the actors on screen. Clips were shown within a window that occupied 45% and 42% of a 15" screen's width, respectively. Narratives were verbal descriptions of the action that took place in each film clip. Five written sentences were presented one at a time (for 6 sec each) in the middle of a white screen (Courier New, Black, Font 18). A male voice-over played simultaneously so that sentences were also read to the participant. Each LE title, which served later as in-scan retrieval cue, was displayed on screen for 2 sec immediately before and after the LE was presented. Participants were instructed to try to remember the title as well as what took place in the story. They were shown the entire sequence of 40 LEs twice, consecutively. Each time, blocks of three narratives were presented in alternation with blocks of three clips (for a total of six blocks for each condition), and the remaining two narratives and clips were presented last. The order in which LEs were presented was randomized across participants. LE encoding lasted approximately 45 min. After encoding, participants completed a pre-scan retrieval practice session that included two practice LEs (one clip and one narrative) and a practice AM.

Actual retrieval took place while participants underwent fMRI. The condition was announced on screen for 2 sec ("Autobiographical Memory", "Laboratory Event", or "Counting"), followed by two consecutive trials from that condition.

**Table 1 – Mean demographic and neuropsychological characteristics per group.**

|  | Controls<br>( $n = 12$ ) | R-mTLE<br>( $n = 12$ ) | Norms                   |
|--|--------------------------|------------------------|-------------------------|
| Gender (M/F)                                 | 5M/7F                    | 6M/6F                  | n/a                     |
| Age in years                                 | 37.4 (10.7)              | 37.2 (14.5)            | n/a                     |
| Years of education                           | 16.9 (3.4)               | 13.8 (2.5)             | n/a                     |
| WASI full scale IQ                           | n/a                      | 107.2 (6.2)            | 100 (15) <sup>a</sup>   |
| Performance IQ                               | n/a                      | 104.6 (8.1)            | 100 (15) <sup>a</sup>   |
| Verbal IQ                                    | n/a                      | 107.9 (8.2)            | 100 (15) <sup>a</sup>   |
| WASI matrix reasoning subtest (scaled score) | 13.4 (1.1)               | 11.5 (1.5)             | 10 (3) <sup>a</sup>     |
| RAVLT total recall score                     | n/a                      | 45.5 (9.2)             | 53.6 (8.3) <sup>b</sup> |
| RVDLT total recall score                     | n/a                      | 38.6 (10.2)            | 46.6 (9.3) <sup>c</sup> |
| Warrington Words                             | n/a                      | 47.3 (1.9)             | 45.7 (4.8) <sup>d</sup> |
| Warrington Faces                             | n/a                      | 39.7 (4.9)             | 43.9 (3.6) <sup>d</sup> |

Standard deviation is between parentheses. Norms were obtained from 30–39 years old from <sup>a</sup> Wechsler (1999), <sup>b</sup> Schmidt (2010), <sup>c</sup> Spreen and Strauss (1991), and <sup>d</sup> Warrington (1984). F = female; M = male; n/a = not applicable; IQ = Intellectual Quotient; RAVLT = Rey Auditory Verbal Learning Test, R-mTLE = right medial temporal lobe epilepsy; RVDLT = Rey Visual Design Learning Test; WASI = Wechsler Abbreviated Scale of Intelligence.

Each trial started with a 1 sec fixation cross. During the control condition (counting), participants were instructed to count backward for 16 sec, by intervals of three, from a given number, followed immediately by a 1 sec inter-stimulus interval (ITI). This task was chosen as a baseline condition to help prevent mind-wandering (Stark & Squire, 2001). During memory trials, a memory title (AM or LE) was shown for 16 sec as a retrieval cue. For AM trials, participants were instructed to re-experience their personal memory in as much detail as possible over those 16 sec. For LE trials, they were told to recount silently what took place in the story, from beginning to end. LEs encoded as narratives and clips were intermixed randomly in the LE condition. Pilot testing indicated that most participants took under 13 sec to recall an entire LE, and so 16 sec was a sufficient time window for participants to complete their recall. Memory trials were followed by ratings for *story content* (4 sec) and *vividness* (4 sec), and then by a 1 sec ITI. Participants performed their ratings on 1–4 Likert scales using a 4 button MR-compatible response keypad. For Story Content ratings, 1 equaled “no LE/AM details”, and 4 corresponded to “all the LE details/my most detailed AMs (in the context of this task).” For vividness ratings, 1 equaled “no visual/perceptual details”, and 4 corresponded to “my most vivid LEs/AMs (in the context of this task).” Vividness was defined to participants as the totality of sensory details (visual, auditory, olfactory, gustatory, tactile, proprioceptive, etc.) they experienced while recalling a memory. Participants completed five functional runs of 436 sec (7 min 16 sec), each of which contained four AM, four Counting and eight LE (narrative and clip intermixed) trials. In-scan trials were presented using E-Prime 1.2 (Psychology Software Tools Inc.) and scanner-compatible goggles (Resonance Technology Inc., CA). Prescription-appropriate corrective lenses were inserted inside the goggles if needed.

A final retrieval session took place outside the scanner on a Lenovo T500 laptop using E-Prime 2.0. The condition was announced on screen (“Autobiographical Memory” or “Laboratory Event”), followed by two consecutive trials from that condition. Each AM or LE was cued by its title. For each memory, participants were recorded while describing (for a maximum of 90 sec) all the story elements they remembered retrieving during the in-scan trial. Each memory was assigned to mini-blocks of 2 AMs or 2 LEs (clips and narratives intermixed). On average, the post-scan retrieval session took around 45 min to complete. It was performed by 10/12 participants with mTLE (two of whom completed 1/5 and 3/5 of the session, respectively) and by 13/14 control participants.

### 2.3. Image acquisition

All images were acquired with a 3-Tesla Signa MR System (GE Medical Systems) at the Toronto Western Hospital. Anatomical images (T1-weighted sequence; TR = 7.876 msec; TE = 3.06 msec; 146 slices, 220 mm FOV, 256 × 256 matrix, .859 × .859 × 1.0 mm voxels) were acquired first, followed by five EPI runs. EPI slices were acquired in an interleaved order in an oblique orientation perpendicular to the long axis of the hippocampus (218 frames per run; TR = 2 sec; TE = 30 msec; 32 slices for 11 participants, and 34 slices for 3 participants, 240 mm FOV, 64 × 64 matrix, resulting in voxel sizes of 3.75 × 3.75 × 5.0 mm). The first three frames of each run were

dropped for signal equilibrium. A multi-echo T2-weighted sequence was acquired at the end of the session.

### 2.4. fMRI analysis

Functional scans were re-aligned within and between runs, co-registered to the anatomical scan, and smoothed with an 8 mm kernel using SPM8 (Statistical Parametric Mapping 8; Welcome Department of Imaging Neuroscience). We used the Artifact Detection Tools software (Whitfield-Gabrieli & Mozes, 2010) to regress out within-run motion parameters, and to identify and regress out frames in which too much head motion was recorded (>.8 mm in linear motion or >.01 radium in rotational motion between frames). All first-level (subject-level) analyses were conducted in native space. For group analyses, subjects' resulting contrast maps were re-sliced (4.0 × 4.0 × 4.0 mm voxels) and normalized to the Montreal Neurological Institute space based on parameters estimated from the normalization of the segmented anatomical scan.

Data were analyzed in SPM8 using a factorial design that modeled the canonical hemodynamic response function. Each trial was analyzed as a mini-block of 5 TRs (10 sec). Piloting revealed that AM retrieval could last the entire 16 sec allocated, but that LE retrieval was completed within 13 sec, on average. To avoid “diluting” the LE trials, we focused our analysis on the first 10 sec of each trial. Beside the onset and duration of correct trials per condition (AM, video, narrative and counting), we also modeled the following task features as variables of no interest: the first portion of unsuccessful trials (10 sec), the announcement of conditions (“Autobiographical Memory”, “Laboratory Event” or “Counting”; 2 sec), the second portion of each trial (successful memory, unsuccessful memory and counting; 6 sec), and the first and second memory ratings (4 sec each).

We first contrasted activity between conditions in the group of healthy controls. For the memory conditions (AM, narratives and clips), only successful trials (Story Content ratings > 1) were entered into the fMRI data analysis. All direct contrasts between the different conditions were performed at a threshold of  $p < .001$ , with a cluster threshold of >10 voxels. This threshold was estimated to correspond to  $p < .05$  corrected at the whole-brain level based on a Monte Carlo simulation conducted using Afni's AlphaSim. To identify voxels activated by all three memory conditions, we conducted a conjunction analysis using an inclusive mask built with xjView (<http://www.alivelearn.net/xjview8>). The mask included all voxels that were significant for each of the following three contrasts: AM > counting, narrative > counting, and clip > counting (each thresholded at  $p < .001$ ). With this approach, voxels that may have fallen below threshold in some contrasts were systematically excluded from the mask (Nichols, Brett, Andersson, Wager, & Poline, 2005). To identify peak coordinates of activation within the inclusive mask, t-values were attributed to voxels based on a second-level SPM analysis conducted within the mask's boundaries that contrasted all three memory conditions to counting in a single contrast. We then contrasted the different memory conditions directly to one another ( $p < .001$ , >10 voxels).

We also contrasted activity between 12 controls and 12 individuals with mTLE. For direct group comparisons at the whole-brain level, we adopted a threshold of  $p < .005$ , with a cluster threshold of  $>20$  voxels, which corresponds to a corrected threshold of  $p < .05$  based on an AlphaSim Monte Carlo simulation. We also performed group comparisons restricted to bilateral hippocampal voxels delineated by a mask created in SPM2's MARINA toolbox (MAAs for Region of INterest Analysis; Bertram Walter, Bender Institute of Neuroimaging, University of Giessen); we adopted a threshold of  $>14$  voxels at  $p < .05$ , which corresponded to a corrected threshold of  $p < .05$  based on AlphaSim.

## 2.5. Parametric fMRI analyses

We conducted a within-subject parametric analysis of hippocampal activation based on automated word counts from post-scan recall data. As only eight individuals with mTLE completed the full post-scan session, this analysis was only performed in the control group. Transcripts of participants' post-scan description of each memory retrieved in-scan were entered into the Linguistic Inquiry and Word Count program (LIWC), which performed an automated count for words falling under 80 different categories defined by an integrated dictionary (LIWC2007; Pennebaker et al., 2007). At the single subject level, we correlated word counts from LIWC's *Perceptual Processes* category, an indicator of perceptual memory content (St-Laurent et al., 2014), with trial-specific levels of hippocampal activation separately for each memory condition using SPM8. We used a factorial design for which trial-specific counts of *Perceptual Processes* words were entered as parametric modulators; parameters of no-interest included those entered in the univariate analysis described above, with the addition of a few trials for which no LIWC output was recorded. As in the analyses described above, unsuccessful trials (Story Content ratings = 1) were excluded. Data from two participants were excluded from the word count analysis: the first participant did not complete the post-scan task, and the other had too few successful trials for this analysis because two of her runs were spoiled by excessive motion. The analysis was restricted to hippocampal voxels delineated with a bilateral hippocampal mask ( $p < .05$ , clusters  $> 14$  voxels; total alpha  $< .05$  based on a Monte Carlo simulation conducted with AlphaSim).

In individuals with right mTLE, we performed a between-subject parametric analysis to identify brain regions whose activity level was modulated by the degree of right hippocampal atrophy. Left and right hippocampal volumes were quantified using Freesurfer v4.5.0 (Athinoula A. Martinos Center for Biomedical Imaging, <http://surfer.nmr.mgh.harvard.edu/>) based on participants' T1-weighted anatomical images. Freesurfer performed a fully automated parcellation and identification of subcortical structures that included the hippocampus proper (Fischl et al., 2002, 2004). This segmentation procedure has been shown to be as reliable as manual rating (Fischl et al., 2002), and to yield reliable measures of hippocampal volume even in individuals with mTLE whose hippocampus is atrophied (Pardoe, Pell, Abbott, & Jackson, 2009).

**Table 2 – Mean ratings and number of correct trials per group for each condition.**

|                        | Controls           | mTLE              |
|------------------------|--------------------|-------------------|
| # Correct trials (/20) | $n = 14$           | $n = 12$          |
| AM                     | 19.86 (.36)        | 19.67 (.65)       |
| Clip                   | 19.64 (.63)        | 19.67 (.65)       |
| Narrative              | 19.29 (1.20)       | 18.33 (2.06)      |
| Story Content rating   | $n = 14$           | $n = 12$          |
| AM                     | 3.07 (.41)         | 3.32 (.45)        |
| Clip                   | 3.47 (.37)         | 3.43 (.46)        |
| Narrative              | 3.15 (.29)         | 2.95 (.45)        |
| Vividness rating       | $n = 14$           | $n = 11$          |
| AM                     | 3.01 (.51)         | 3.36 (.33)        |
| Clip                   | 3.36 (.43)         | 3.59 (.41)        |
| Narrative              | 2.58 (.57)         | 2.87 (.40)        |
| LIWC word count        | $n = 13$           | $n = 10$          |
| AM                     | 3.12 (2.33)        | 2.46 (1.91)       |
| Clip*                  | <b>3.93 (1.78)</b> | <b>2.20 (.90)</b> |
| Narrative*             | <b>2.21 (1.25)</b> | <b>1.15 (.54)</b> |

Standard deviation is between parentheses. Only correct trials (Story Content rating  $> 1$ ) were included in the calculation of the mean ratings and LIWC word count. One participant with mTLE did not provide consistent vividness ratings.

\* $p < .05$  for direct group comparisons (2-sample t-tests). Significant group comparisons are shown in bold.

For each participant with mTLE, we quantified hippocampal volume asymmetry (HVA) by dividing right hippocampal volume by left hippocampal volume (both in  $\text{mm}^3$ ). This measure controlled for individual differences in brain morphology by using the left, non-epileptogenic hippocampus as the baseline.<sup>1</sup> HVA differed significantly between the 12 individuals with mTLE (mean = .85, SD = .16) and the 14 controls [mean = 1.01, SD = .05;  $t(24) = 3.636$ ,  $p = .001$ ], indicating significant right hippocampal atrophy in the mTLE group. To identify brain regions whose activity level was modulated by right hippocampal atrophy in the mTLE group, we performed three between-subject parametric analyses (one for each memory condition). Contrasts between the memory condition (AM, narrative or clip) and the counting condition were entered into a group-level analysis (t-test), and HVA was entered as a covariate ( $p < .005$ , clusters  $> 20$  voxels; total alpha  $< .05$  based on an AlphaSim Monte Carlo simulation).

## 3. Results

### 3.1. Behavioral results

The mean number of trials retrieved successfully (Story Content rating  $> 1$ ) was high across conditions in both the control and the mTLE group (Table 2). The number of successful trials was slightly reduced in the narrative compared to the other two conditions in the mTLE group, although this difference did not survive when adjusted for multiple comparisons (see

<sup>1</sup> Note that one participant had 30% of seizures originating from the left rather than the right hippocampus. His HVA was 1.006 and his hippocampi were described as normal by a neuroradiologist.

Supplementary Material for statistical comparisons). Only successful trials (Story Content ratings > 1) were included in the fMRI analyses.

Previous evidence indicates that ratings are poor indicators of memory deficits in mTLE (Addis, 2005; St-Laurent et al., 2014). Fittingly, Story Content and Vividness ratings did not differ significantly between groups in any of the conditions (all uncorrected  $p$ 's > .066), although significant differences emerged between conditions (complete analyses in Supplementary Material). A 3-way repeated-measure ANOVA conducted over groups, ratings and the two laboratory event conditions indicated that differences in ratings between the clip and the narrative condition (clip > narrative) were larger for Vividness ratings than for Story Content ratings [ratings  $\times$  condition interaction effect,  $F(1, 23) = 15.47$ ,  $p < .001$ ]. This pattern did not differ significantly between the two groups [non-significant group  $\times$  condition  $\times$  rating interaction effect:  $F(1, 23) = 1.06$ ,  $p = .314$ ]. Thus, in both groups, the difference between the narrative and clip condition was significantly greater for Vividness than for Story Content ratings, indicating a perceived lack of vividness in the perceptually impoverished narrative condition.

We report mean word counts from the LIWC Perceptual Processes category to characterize perceptual richness across groups and conditions (Table 2 and Supplementary Fig. S2; successful trials with complete recordings only). Previously, we showed that this automated measure is sensitive to memory deficits in mTLE and is consistent with manual counts of perceptual memory details (St-Laurent et al., 2014). A two-way ANOVA contrasting word counts between groups for the two laboratory conditions revealed significant main effects of condition [clip > narrative,  $F(1, 21) = 53.146$ ,  $p < .001$ ] and group [control > mTLE,  $F(1, 21) = 8.015$ ,  $p = .010$ ]. The numerically greater discrepancy between the perceptually rich and impoverished conditions observed in the controls was not significant, as indicated by a non-significant group  $\times$  condition interaction effect [ $F(1, 21) = 2.803$ ,  $p = .109$ ]. Also, word counts were numerically greater in controls than in patients in the AM condition, although this difference was not significant [ $t(21) = .729$ ,  $p = .474$ ].

Differences between groups and conditions were consistent with, but more subtle than those we observed in our previous behavioral study (Supplementary Section S3), which was conducted on similar cohorts of controls and patients; a few factors account for these discrepancies. Firstly, only eight participants with mTLE completed the current post-scan session in full (means were computed from partial data for two mTLE participants). Secondly, participants described twice as many memories as in the previous study, after 3 h of testing in and outside the scanner, and testing fatigue most likely contributed to lower word counts (e.g., mean perceptual word count for AM in controls: current study = 3.12 words/memory; previous study = 9.73 words/memory; Supplementary Fig. S2). Thirdly, participants were only instructed to report story elements (i.e., what happened). In the previous study, participants were also questioned explicitly about perceptual memory details, but we omitted this question to reduce overall testing time. Consequently, any mention of perceptual content in the current study was

incidental, and the current LIWC results offer a somewhat limited portrayal of perceptual memory content.

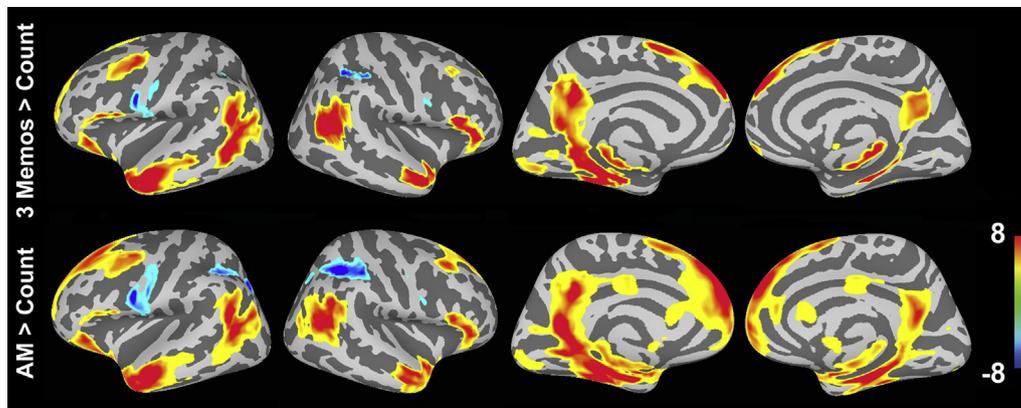
To provide what we believe is a more accurate characterization of memory content per group and condition, we re-analyzed data from similar cohorts of controls and patients with right mTLE who participated in our previous behavioral study (St-Laurent et al., 2014; results are shown in Supplementary Material Section S3 and Fig. S2). Briefly, LIWC word counts as well as manual counts of story and perceptual details were significantly lower in mTLE participants compared to controls in every memory condition [2-sample  $t$ -tests;  $t(32) \geq 2.464$ ,  $p \leq .019$ ]. Story detail counts indicated that story content (i.e., the gist of the memory) did not differ significantly between the narrative and clip conditions in either controls or participants with right-lateralized mTLE [two-by-two ANOVA; main effect of condition:  $F(1, 32) = .493$ ,  $p = .4875$ ; group  $\times$  condition interaction effect:  $F(1, 32) = 3.011$ ,  $p = .0923$ ]. However, LIWC word counts and manual counts of perceptual details—our two measures of perceptual memory content—were significantly greater for clips than for narratives [separate two-by-two ANOVAs, main effect of condition for perceptual details:  $F(1, 32) = 42.130$ ,  $p < .001$ ; for LIWC:  $F(1, 32) = 17.933$ ,  $p < .001$ ]. Moreover, this discrepancy was larger in controls than in individuals with mTLE [group  $\times$  condition interaction effect for perceptual details:  $F(1, 32) = 37.460$ ,  $p < .001$ ; for LIWC:  $F(1, 32) = 3.447$ ,  $p = .073$ ]. These results indicate that perceptual richness was reduced disproportionately in the clip condition in the mTLE group. Finally, a contrast between story and perceptual details in the AM condition indicated a significantly larger deficit for perceptual relative to story details in the mTLE group [two-by-two ANOVA, group  $\times$  detail type interaction effect,  $F(1, 32) = 4.189$ ,  $p = .049$ ]. Thus, while mTLE reduces memory for all kinds of AM details, it affects perceptual content disproportionately compared to story elements.

These results guide our interpretation of differences in brain activation elicited by the retrieval of AM, clips and narratives in the current study. In healthy individuals, a contrast between brain activity elicited during the clip and the narrative conditions should reflect differences in perceptual but not in story content. Also, neural signal that reflects perceptual richness should differ to a lesser extent between clips and narratives in individuals with mTLE compared to controls.

### 3.2. fMRI results in 14 healthy controls

#### 3.2.1. Common memory regions

The conjunction analysis identified a large set of regions engaged by each of the three memory conditions in comparison to the counting condition (Fig. 1 and Table 3). These regions included the posterior cingulate cortex, the inferior, middle and superior frontal gyri including the medial prefrontal cortex, the angular portion of the inferior parietal lobule, the temporal poles, medial temporal regions including the bilateral hippocampus (Fig. 2, 1st row) and parahippocampal cortex, and the left lingual gyrus and caudate nucleus. Regions activated to a greater extent by counting than by the three memory conditions, which were identified by the opposite analysis, included the precentral gyrus and



**Fig. 1** – Top row: Conjunction analysis in 14 controls. An inclusive mask identified voxels significant for separate contrasts between each memory condition (AM, narrative or clip) and the control counting condition [ $t(13) > 4.22$ ,  $p < .001$  for each contrast]. Within the inclusive mask, voxel values were determined by a single contrast between all three memory conditions and counting (warm colors: memory > counting; cold colors: counting > memory). Bottom row: contrast between the AM and the counting condition [ $t(13) > 4.22$ ;  $p < .001$ ; warm colors: AM > counting; cold colors: counting > AM]. Count = counting condition, 3 Memos = three memory conditions.

**Table 3** – Brain regions engaged during all three memory conditions compared to counting.

| Region                              | Hemi | BA    | Clu. Size | t-Score | MNI coordinates |     |     |
|-------------------------------------|------|-------|-----------|---------|-----------------|-----|-----|
|                                     |      |       |           |         | x               | y   | z   |
| <i>Memory &gt; Counting</i>         |      |       |           |         |                 |     |     |
| Parahippocampal gyrus               | R    | 28/35 | 1884      | 14.64   | 22              | –24 | –22 |
| **Hippocampus                       | R    | n/a   | 1884      | 13.14   | 22              | –20 | –18 |
| *Fusiform gyrus                     | L    | 20/37 | 1884      | 11.55   | –34             | –40 | –22 |
| *Middle temporal gyrus              | L    | 21    | 1884      | 11.25   | –54             | –4  | –26 |
| **Hippocampus                       | L    | n/a   | 1884      | 9.54    | –30             | –20 | –18 |
| Medial prefrontal cortex            | R    | 9     | 691       | 13.58   | 6               | 56  | 26  |
| *Medial prefrontal cortex           | L    | 9     | 691       | 10.67   | –10             | 56  | 26  |
| Middle temporal gyrus               | R    | 21    | 226       | 13.25   | 54              | 0   | –18 |
| *Inferior frontal gyrus (p. triang) | R    | 45    | 226       | 10.25   | 54              | 24  | 18  |
| Middle temporal/angular gyrus       | R    | 39    | 223       | 10.22   | 46              | –56 | 18  |
| Precentral/middle central gyrus     | L    | 6     | 100       | 8.15    | –42             | 8   | 42  |
| Caudate nucleus                     | L    | n/a   | 33        | 7.44    | –10             | 8   | 10  |
| Gyrus rectus                        | R    | 11    | 19        | 7.03    | 6               | 56  | –18 |
| Lingual gyrus                       | L    | 18    | 94        | 6.49    | –10             | –84 | –10 |
| <i>Counting &gt; Memory</i>         |      |       |           |         |                 |     |     |
| Precentral gyrus                    | L    | 6     | 50        | 10.29   | –54             | 4   | 22  |
| Intraparietal sulcus                | R    | 40    | 33        | 7.49    | 34              | –44 | 42  |
| Intraparietal sulcus                | L    | 40    | 12        | 6.26    | –38             | –44 | 38  |
| Precentral gyrus                    | R    | 6     | 15        | 6.21    | 54              | 4   | 18  |

All activations are significant at  $p < .001$  [uncorrected;  $t(13) > 4.22$ ; cluster threshold > 10 voxels], which corresponds to a whole-brain alpha of < .05 based on a Monte Carlo simulation conducted with AFNI's AlphaSim. The cluster's Brodmann Area (BA) and the coordinates (MNI space, in mm) and t-value of the voxel with the highest t-value ("peak voxel") per cluster are provided. Hemi = Hemisphere, L = Left, MNI = Montréal Neurological Institute, R = Right. \*Local maxima > 8 mm from peak voxel; \*\*Local maxima identified within a hippocampal mask.

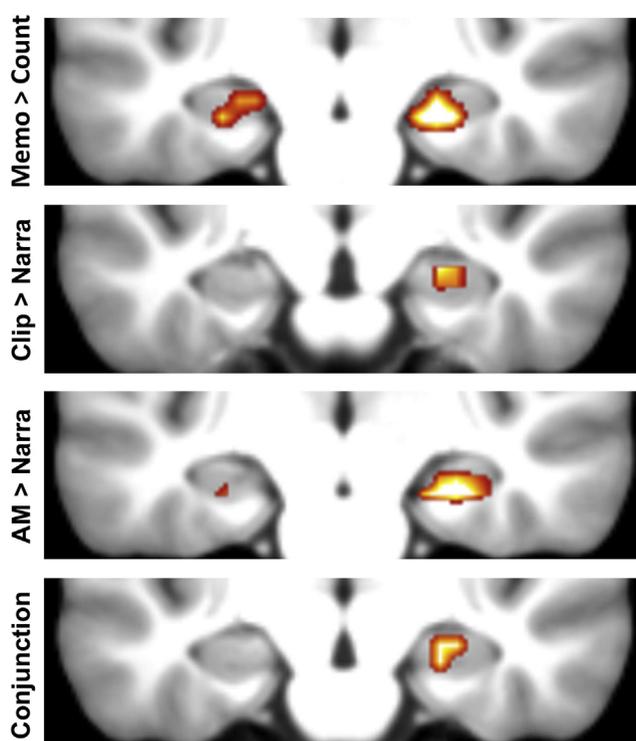
the intraparietal sulcus bilaterally (cold colors on Fig. 1 and Table 3; within an inclusive mask of voxels with significantly greater activation during counting than during each memory condition, we identified peak voxels with a single contrast between counting and the three memory conditions).

Importantly, we observed extensive overlap between regions identified by the conjunction analysis, and regions engaged during AM retrieval (in comparison to counting; Fig. 1, bottom row). Displaying the conjunction and the AM analyses side by side illustrates how our laboratory tasks engaged several regions from the canonical AM retrieval

network (angular gyrus, retrosplenial/posterior cingulate cortex, temporal pole, MTL) to a degree comparable to the AM task, although laboratory tasks did not engage the medial prefrontal cortex as reliably as AM. These results confirm that our laboratory tasks can be used to address questions about the engagement of the AM network.

### 3.2.2. Contrasts between the memory conditions

A direct comparison between the video and the narrative conditions, which were well matched for several characteristics of no interest to the current analysis but differed



**Fig. 2 – Patterns of activation within a hippocampal mask in 14 controls. 1st row: voxels significant for each of the three memory conditions (“Memo”: AM, narratives and clips) in comparison to counting [“Count”;  $t(13) > 4.22$ ,  $p < .001$  for each contrast]. 2d row: clips > narratives [“Narra”;  $t(13) = 4.22$ ,  $p < .001$ ]. 3rd row: AM > narratives [ $t(13) = 4.22$ ,  $p < .001$ ]. 4th row: conjunction analysis indicating significant voxels for both the clips > narratives [ $t(13) = 4.22$ ,  $p < .001$ ] and the AM > narratives [ $t(13) = 4.22$ ,  $p < .001$ ] contrasts that did not reach significance for either the AM > clips [ $t(13) = 2.17$ ,  $p < .05$ ] or the clips > AM [ $t(13) = 2.17$ ,  $p < .05$ ] contrasts. Note that the clips > narratives contrast did not reveal significant clusters (>14 voxels) in the left hippocampus even at a lower threshold (e.g.,  $p < .05$ ).**

substantially in perceptual content, revealed brain regions whose activity was modulated by perceptual richness during recall. Only regions with greater activity for clips than for narratives were identified by this contrast, as no regions were significantly more active for narratives. As hypothesized, we observed significant activation within the hippocampus, which was lateralized to the right hemisphere (Fig. 2, 2nd row). Outside of the hippocampus, the pattern of activity identified by this contrast was also more prominent in the right hemisphere, and included the right parahippocampal gyrus, fusiform gyrus (right > left), angular gyrus and middle occipital gyrus, as well as midline structures such as the medial prefrontal cortex and the retrosplenial cortex extending into the precuneus (Fig. 3, top row; Table 4).

A direct comparison between the narrative and the AM conditions (Fig. 2, 3rd row; Fig. 3, middle row; Supplementary Table S1) identified regions whose activity was greater for AM than for the narrative condition, which included the bilateral

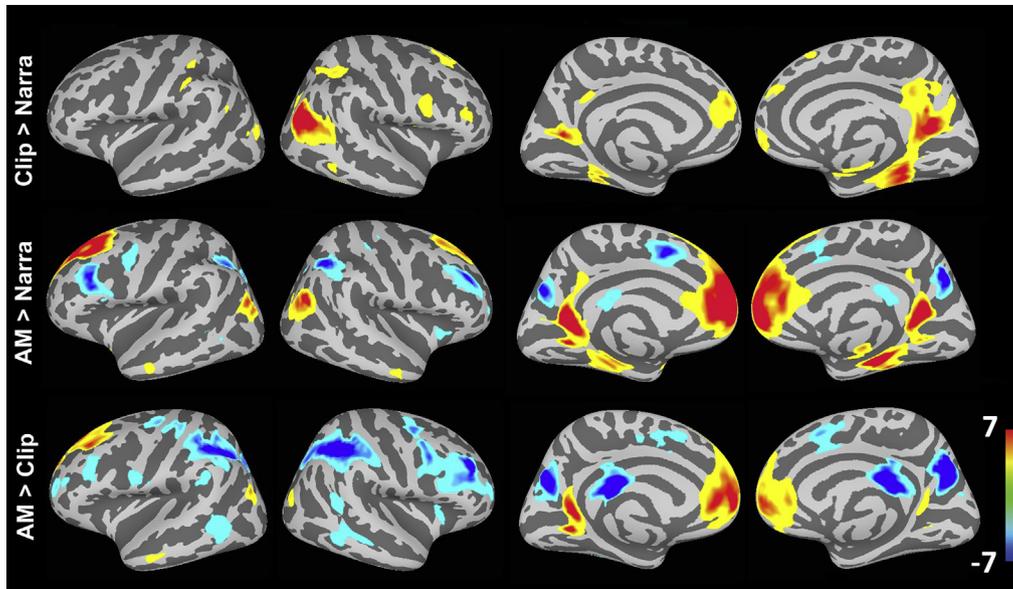
hippocampus (right > left; Table 5) and parahippocampal cortex, the medial prefrontal and retrosplenial cortex, as well as the angular gyrus and middle occipital gyrus. Many of these regions were similar to those showing greater activation for clips than for narratives, with the notable exception of the widespread difference in medial prefrontal activation unique to the current contrast (Fig. 3). Regions more active for narratives than for AM included the middle frontal gyrus, the precuneus (posterior to the region identified by the clip > narrative contrast), the intraparietal sulcus and the left supplementary motor area (SMA).

Contrasting the AM and the clip conditions (Fig. 3, 3rd row; Supplementary Table S2), which were both rich in perceptual details, did not reveal any significant difference in hippocampal activation, even at a lenient threshold (e.g.,  $p < .05$ ). Regions activated to a greater extent by AM than by the clip condition included midline structures such as the retrosplenial cortex and medial prefrontal cortex extending into the superior frontal gyrus, and the left angular gyrus. Regions activated to a greater extent by clips than AM included the middle frontal gyrus, precuneus, intraparietal sulcus and right SMA (all regions close to those identified by the narrative > AM contrast). Thus, although both LEs engaged many of the structures that form the AM retrieval network, the AM condition elicited greater activation in the medial prefrontal and retrosplenial cortex than either of the two laboratory conditions, perhaps reflecting greater personal relevance and scene construction. On the other hand, both LEs recruited the precuneus, SMA, ventro-lateral prefrontal cortex and intraparietal sulcus to a greater extent than the AM condition, which may have reflected differences in attentional demands at retrieval between laboratory and naturalistic tasks.

As hypothesized, hippocampal activation was greater during the retrieval of perceptually rich AMs and clips compared to perceptually impoverished narratives. This pattern of activation was strongly right-lateralized, and did not differ significantly between the AM and clip conditions. A conjunction analysis identified hippocampal voxels that were significant for both the clips > narratives ( $p < .001$ ) and the AM > narratives ( $p < .001$ ) contrasts but did not reach significance for either the AM > clips [ $t(13) = 2.17$ ,  $p < .05$ ] or the clips > AM [ $t(13) = 2.17$ ,  $p < .05$ ] contrasts. Only one cluster of right hippocampal voxels met these criteria (Fig. 2, bottom row).

### 3.2.3. LIWC parametric analysis

In 12 control participants, we performed within-subject parametric analyses correlating trial-specific LIWC Perceptual Processes word counts and activation within a mask that delineated hippocampal voxels. In the clip condition, activity in a cluster of right hippocampal voxels correlated positively with Perceptual Processes word counts (Table 5). No such effect was observed in the narrative condition. Correlations were also observed in a few right hippocampal voxels in the AM condition, although this cluster was too small (5 voxels) to be considered significant at  $\alpha < .05$ . As discussed above, there were several limitations with the current LIWC data. Nevertheless, our results indicate a relationship between right hippocampal activation and perceptual memory content in the clip condition, and a trend in the anticipated direction in the AM condition.



**Fig. 3** – Contrasts among the three memory conditions in 14 controls. Top: clips > narratives; middle: AM > narratives; bottom: AM > clips [ $t(13) = 3.38$ ,  $p < .005$ ]. We selected a lower threshold than for coordinate tables ( $p < .001$ ) to display a range of significance values [up to  $t(13) \geq 7$ ].

**Table 4** – Regions whose activity differed between the film clip and the narrative conditions.

| Region                            | Hemi | BA    | Clu. Size | t-Score | MNI coordinates |     |     |
|-----------------------------------|------|-------|-----------|---------|-----------------|-----|-----|
|                                   |      |       |           |         | x               | y   | z   |
| <i>Film Clips &gt; Narratives</i> |      |       |           |         |                 |     |     |
| Middle occipital/angular gyrus    | R    | 19/39 | 316       | 10.97   | 46              | -72 | 26  |
| *Retrosplenial cortex             | R    | 29/30 | 316       | 8.01    | 14              | -56 | 18  |
| *Retrosplenial cortex             | L    | 29/30 | 316       | 7.02    | -18             | -60 | 14  |
| Parahippocampal/fusiform gyrus    | R    | 36/37 | 165       | 7.25    | 30              | -44 | -10 |
| *Hippocampus                      | R    | n/a   | 165       | 5.53    | 22              | -8  | -14 |
| *Hippocampus                      | R    | n/a   | 165       | 4.72    | 22              | -20 | -18 |
| Medial frontal cortex             | L    | 9/32  | 22        | 5.87    | -6              | 52  | 14  |
| Fusiform gyrus                    | L    | 37    | 25        | 5.61    | -30             | -40 | -14 |
| Posterior cingulate cortex        | R    | 31    | 23        | 5.51    | 6               | -40 | 38  |

All activations are significant at  $p < .001$  [uncorrected;  $t(13) > 4.22$ ; cluster threshold > 10 voxels], which corresponds to a whole-brain alpha of  $< .05$  based on a Monte Carlo simulation conducted with AFNI's AlphaSim. The cluster's Brodmann Area (BA) and the peak voxel's coordinates (MNI space, in mm) and t-value are provided. Hemi = Hemisphere, L = Left, MNI = Montréal Neurological Institute, R = Right. \*Local maxima > 8 mm from peak voxels.

### 3.3. fMRI results in 12 individuals with mTLE and 12 healthy controls

#### 3.3.1. Difference in hippocampal activation between the groups

We contrasted brain activity elicited by each memory condition (in comparison to the baseline; e.g., AM > counting) between the two groups. At the whole-brain level (>20 voxels,  $p < .005$  uncorrected), no cluster was significant in any condition. However, similar comparisons restricted to hippocampal voxels for which we used a threshold corrected for small volumes (>14 voxels,  $p < .05$  uncorrected) revealed significantly greater levels of right (but not left) hippocampal activation in the controls compared to individuals with right mTLE in all three memory conditions (Table 6 and Supplementary Fig. S3). These results indicate relatively preserved levels of cortical activation in the mTLE group, in addition to reduced activation in the hippocampus affected by their condition.

#### 3.3.2. Group differences in signal that reflects perceptual memory content

Based on current and previous patterns of behavioral results, we hypothesized that neural signal that reflects perceptual memory content should be reduced in the mTLE group. First, we contrasted activity between the (perceptually rich) clip and (perceptually impoverished) narrative conditions within each group (Fig. 4, top and middle row). A visual inspection of these results suggests that perceptual memory signal was reduced in the mTLE group in comparison to the control group. To test this effect, we compared the clip > narrative contrast directly between the two groups. We identified a cluster of voxels in the right middle occipital cortex [56 voxels; peak voxel  $t(22) = 5.57$ , MNI coordinates:  $x = 50$ ,  $y = -72$ ,  $z = 26$ ] whose “boost” in activity in the clip relative to the narrative condition—an index of perceptual memory content—was significantly reduced in the mTLE group compared to controls (Fig. 4, bottom row).

**Table 5 – Significant hippocampal voxel counts as a function of condition and perceptual memory content in a group of 14 controls.**

| Analysis                                | Hemi | Vox. Count | t-Score     | MNI coordinates |     |     |
|---|------|------------|-------------|-----------------|-----|-----|
|   |      |            |             | x               | y   | z   |
| <i>Task contrasts (n = 14 controls)</i> |      |            |             |                 |     |     |
| <i>Film Clips &gt; Narratives</i>       |      |            |             |                 |     |     |
|   | R    | <b>15*</b> | <b>5.48</b> | 22              | –12 | –14 |
|   | L    | 1          | 4.38        | 18              | –28 | –10 |
| <i>AM &gt; Narratives</i>               |      |            |             |                 |     |     |
|   | R    | <b>26*</b> | <b>9.00</b> | 26              | –20 | –18 |
|   | L    | 3          | 5.17        | –30             | –20 | –18 |
| <i>LIWC (n = 12 controls)</i>           |      |            |             |                 |     |     |
| <i>Film clips</i>                       |      |            |             |                 |     |     |
|   | R    | <b>47*</b> | <b>3.07</b> | 26              | –20 | –14 |
|   | L    | 3          | 1.84        | 14              | –36 | 2   |
| <i>AM</i>                               |      |            |             |                 |     |     |
|   | R    | 5          | 2.04        | 18              | –28 | –10 |
|   | L    | 1          | 1.71        | –18             | –24 | –10 |

For task contrasts, we adopted the threshold for whole-brain contrasts [ $t(13) > 4.23$ ,  $p < .001$  2-tail uncorrected, clusters  $> 11$  voxels, whole-brain alpha  $< .05$ ]. For LIWC analyses restricted to the hippocampus, we used a small volume correction [ $t(11) > 1.80$ ,  $p < .05$  1-tail uncorrected, clusters  $> 14$  voxels, whole-volume alpha  $< .05$ ]. Hemi = Hemisphere, Vox = Voxels.  
\*Significant,  $p < .05$  corrected.  
Significant clusters are listed in bold.

**Table 6 – Significant hippocampal voxel counts as a function of group and condition in 12 individuals with right-lateralized mTLE and 12 controls.**

| Analysis  | Hemi | Vox. Count | t-Score     | MNI coordinates |     |     |
|---|------|------------|-------------|-----------------|-----|-----|
|   |      |            |             | x               | y   | z   |
| <i>Group contrasts per memory task (12 controls &gt; 12 mTLE)</i> |      |            |             |                 |     |     |
| <i>Film Clips &gt; Counting</i>                                   |      |            |             |                 |     |     |
|   | R    | <b>18*</b> | <b>3.40</b> | 18              | –28 | –10 |
|   | L    | 0          | –           | –               | –   | –   |
| <i>Narratives &gt; Counting</i>                                   |      |            |             |                 |     |     |
|   | R    | <b>38*</b> | <b>3.87</b> | 14              | –28 | –10 |
|   | L    | 0          | –           | –               | –   | –   |
| <i>AM &gt; Counting</i>   |      |            |             |                 |     |     |
|   | R    | <b>33*</b> | <b>3.90</b> | 22              | –20 | –18 |
|   | L    | 0          | –           | –               | –   | –   |
| <i>Film clips &gt; Narratives contrast</i>                        |      |            |             |                 |     |     |
| <i>Within 12 controls</i>   |      |            |             |                 |     |     |
|   | R    | <b>89*</b> | <b>5.45</b> | 22              | –12 | –14 |
|   | L    | 0          | –           | –               | –   | –   |
| <i>Within 12 mTLE</i>   |      |            |             |                 |     |     |
|   | R    | <b>43*</b> | <b>3.73</b> | 34              | –28 | –14 |
|   | L    | <b>30*</b> | <b>3.74</b> | –30             | –4  | –26 |
| <i>12 Controls &gt; 12 mTLE</i>                                   |      |            |             |                 |     |     |
|   | R    | 0          | –           | –               | –   | –   |
|   | L    | 6          | –1.92       | –30             | –4  | –26 |

For all contrasts, we used a small volume correction [whole-volume alpha  $< .05$ , clusters  $> 14$  voxels at  $p < .05$  uncorrected; Between Group Contrasts:  $t(22) = 1.72$ , 1-tail; Within Group Contrast:  $t(11) = 2.21$ , 2-tail]. Hemi = Hemisphere, Vox = Voxel.  
\*Significant,  $p < .05$  corrected.  
Significant clusters are listed in bold.

No significant group difference was observed in the right hippocampus even at a threshold adjusted for small volumes. In fact, both patients and controls activated their right hippocampus to a greater extent when retrieving clips than when retrieving narratives (although right hippocampal activation was reduced significantly in the mTLE group compared to the controls in each memory condition). In patients (but not controls), this difference between conditions also extended to the left hippocampus (Table 6 and Supplementary Fig. S3),<sup>2</sup> possibly reflecting contralateral compensation (although a direct comparison between patients and controls for this left hippocampal signal was not significant, possibly due to low statistical power). Thus, right (and left) hippocampal activation increased when the mTLE group retrieved perceptually rich compared to perceptually impoverished memories. In comparison to the controls, however, this increase in hippocampal activation was associated with weaker recruitment among cortical regions sensitive to perceptual richness in the mTLE group. This pattern of cortical activation is consistent with behavioral evidence that perceptual memory content is poor in mTLE.

### 3.4. Hippocampal volume parametric fMRI analysis in 12 individuals with mTLE

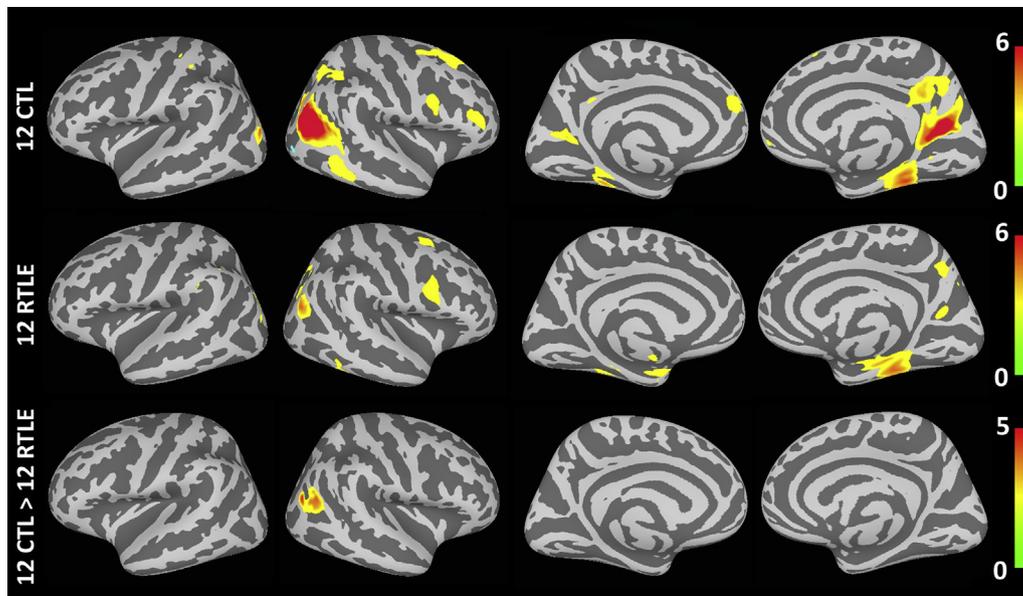
Within the mTLE group, we assessed the impact of right hippocampal atrophy on activation during retrieval. We performed separate parametric analyses in which contrasts between a memory condition and the counting condition were entered for each subject in a group-level analysis, and HVA was entered as a covariate. In the AM and film clip conditions, we identified a cluster whose activity level correlated with right hippocampal volume (more atrophy = less activation) in the right superior temporal cortex bordering the temporo-parietal junction (TPJ). A smaller, non-significant cluster (12 voxels) was also observed in this region in the narrative condition (Supplementary Fig. S4). Additional regions also correlated with right hippocampal volume in the AM but not the other conditions, including the right thalamus, left lingual gyrus and left superior parietal lobule (Supplementary Table S3). None of the regions whose activity reflected perceptual memory content were influenced by hippocampal volume in the current analysis. At a threshold corrected for small volumes [ $> 14$  voxels,  $t(10) = 1.82$ ,  $p < .05$ ], activity in the right (but not left) hippocampus correlated positively with right hippocampal volume in the narrative condition (23 voxels, peak voxel's  $t = 3.14$ , MNI: 18 –8 –14), but not in the clip or AM condition.

## 4. Discussion

### 4.1. Neural correlates of perceptual richness

We designed a memory retrieval task during which both real-life and laboratory events engaged overlapping sets of regions from the canonical AM network (Addis, McIntosh, Moscovitch,

<sup>2</sup> The left hippocampal cluster's peak voxel is located at the anterior tip of the hippocampus, bordering on the left amygdala. However, the cluster extends posteriorly into the hippocampus's head and body.



**Fig. 4 – Contrasts between the clip and narrative conditions (clip > narrative) within and between groups. Within-group contrasts for 12 controls (top row) and 12 mTLE participants (middle row),  $t(11) = 3.11$ ,  $p < .005$ . Bottom row: direct comparison between 12 controls and 12 mTLE participants for the clip > narrative contrast,  $t(22) = 2.82$ ,  $p < .005$ . CTL = controls.**

Crawley, & McAndrews, 2004; Addis, Moscovitch, et al., 2007; Cabeza & St Jacques, 2007; Maguire, 2001a; Svoboda et al., 2006). We manipulated the perceptual richness of our LEs to identify sets of regions whose engagement was modulated by perceptual memory content. Operationally, we defined this “perceptual memory signal” as the difference in activation between rich film clips and impoverished narratives. In a group of healthy controls, this signal was expressed in predominantly right-lateralized regions that included the right hippocampus as well as other posterior cortical regions involved in visual, imagery and spatial processes, such as the middle occipital cortex (Grill-Spector, Kourtzi, & Kanwisher, 2001; Malach et al., 1995), parahippocampal gyrus (Epstein & Kanwisher, 1998; Epstein, Parker, & Feiler, 2007; Litman, Awipi, & Davachi, 2009), perirhinal cortex (Dickerson & Eichenbaum, 2010; Graham, Barense, & Lee, 2010), fusiform gyrus (Kanwisher, McDermott, & Chun, 1997), precuneus (“the mind’s eye”; Cavanna & Trimble, 2006; Fletcher, et al., 1995) and retrosplenial cortex (Vann, Aggleton, & Maguire, 2009). Activation among these “perceptual regions” was consistent with behavioral measures of perceptual content across our different memory conditions: it was reduced for narratives compared to either film clips or AMs, while it was comparable between the latter two conditions. In other words, this pattern of posterior cortical activation provided a neural marker of perceptual memory content that could serve as proxy for behavior.

Our goal was to investigate the relationship between perceptual memory richness and hippocampal function at retrieval. Previously, our group has shown that functional and effective connectivity between the hippocampus and the fusiform and middle occipital gyri during AM retrieval increased from an initial construction phase (during which participants searched for and accessed a personal event) to a

subsequent elaboration phase during which participants were encouraged to re-live that event in detail (McCormick, St-Laurent, Ty, Valiante, & McAndrews, 2015). Together with the current results, these findings suggest that the right hippocampus plays an important functional role in the recruitment of posterior cortical regions that support the representation of perceptual memory content.

To probe this idea further, we assessed whether right hippocampal integrity influenced the magnitude of the perceptual memory signal. In individuals with seizures from right hippocampal origin, we observed a significant signal reduction that was centered around the middle occipital cortex, a region involved in visual processing that is also activated by imagery and vivid retrieval (Buchsbaum, Lemire-Rodger, Fang, & Abdi, 2012; Daselaar, Porat, Huijbers, & Pennartz, 2010; Grill-Spector et al., 2001; Huijbers, Pennartz, Rubin, & Daselaar, 2011; Lehmann, Pascual-Marqui, Strik, & Koenig, 2010; Malach et al., 1995). Against our predictions, the group difference in perceptual memory signal was restricted to the cortex and did not extend to the right hippocampus itself. It must be noted, however, that hippocampal activation does not always increase linearly with memory performance and can, in some instances, reflect compensation (Dickerson et al., 2005; Maguire & Frith, 2003; Sperling et al., 2010) or unsuccessful retrieval attempts (Westmacott, Silver, & McAndrews, 2008). In our study, right hippocampal activation was reduced across conditions in the mTLE compared to the control group (see also Addis, Moscovitch, et al., 2007), but it was significantly greater during clip compared to narrative retrieval within both groups, a task difference that also extended to the left hippocampus in the mTLE group.

In our patients, however, increased right hippocampal activation in the perceptually rich compared to the perceptually impoverished condition most likely reflected attempted

rather than successful retrieval of perceptual details. That is, increased hippocampal signal seemed less effective at recruiting posterior cortical regions in the mTLE group than in the controls, a finding consistent with evidence of reduced connectivity between the epileptogenic MTL and posterior cortical regions in unilateral mTLE (Addis, Moscovitch, et al., 2007; McCormick et al., 2014). The reduced cortical perceptual signal we observed in our patients was also accompanied by a reduction in perceptual processes words tallied from post-scan memory transcripts, a finding consistent with previous evidence that perceptual memory content is reduced in mTLE (Noulhiane et al., 2008; St-Laurent et al., 2009, 2014). As for the increase in left hippocampal activation observed in the mTLE group in the clip compared to the narrative condition, this pattern was absent in the control group and may have reflected compensatory activity, although it was insufficient to result in the activation of cortical perceptual regions, or in the successful recall of perceptual memory details (but see Finke, Bruehl, Duzel, Heekeren, & Ploner, 2013 for left hippocampal compensatory activity that supports associative memory in right-lateralized mTLE). Overall, our results provide a pattern of reduced cortical activation that implies altered connectivity between the right hippocampus and posterior cortical regions, and that accounts for the paucity of perceptual memory content observed in mTLE.

As mentioned, our word count measure was limited in several ways. Nevertheless, a parametric analysis indicated greater right hippocampal activation when healthy controls recalled film clips that received higher perceptual processes word counts, linking hippocampal activation to the retrieval of perceptual details in the healthy brain. No such effect was observed in the narrative or the AM conditions. Anecdotally, participants seemed to refer to perceptual processes more spontaneously to describe their recollection of clips (i.e., “I see a boy with a huge pack back;” “I see two bullies pushing him down”) than of AMs, for which they adopted more of a storytelling style (i.e., “I was walking my dog outside,” rather than “I can see myself walking my dog”). This difference in wording may have accounted for differences in the robustness of the parametric modulation in the clip versus the AM condition.

Within the mTLE group, right hippocampal atrophy correlated negatively with activation in the ventral portion of the right TPJ. This region was anterior to the angular gyrus whose activity was sensitive to perceptual memory content. In fact, none of the perceptual cortical regions were modulated by hippocampal volumes in the mTLE group, and it is unclear whether the TPJ modulation reflected altered retrieval mechanisms that influenced perceptual memory content. Others have also failed to observe correlations between hippocampal volumes and either behavioral memory performance (McCormick et al., 2014) or neural markers of memory representation (Bonnici, Sidhu, Chadwick, Duncan, & Maguire, 2013) within groups of mTLE participants, despite reporting significant deficits at the group level (but see Barnett, Park, Pipitone, Chakravarty, & McAndrews, 2015). Recent mediation analyses conducted in mTLE have revealed that the relationship between structural integrity and memory performance is mediated by measures of functional integrity such as distributed patterns of functional connectivity (McCormick et al., 2014) and local measures of

hippocampal activation (Barnett et al., 2015). Thus, volumes are imperfect predictors of memory performance in mTLE, and functional integrity measures may have been better predictors of perceptual memory content and posterior cortical activation in our patient group.

Despite these limitations, our study provides both between- and within-task evidence that perceptual memory content relies on the engagement and integrity of the right hippocampus during event recall. These results are consistent with evidence from the AM literature indicating that hippocampal activation increases with subjective ratings of imagery levels (Andrews-Hanna et al., 2010; Viard et al., 2007), vividness (Gilboa et al., 2004), reliving (St Jacques, Rubin, & Cabeza, 2012; Viard et al., 2012; but see Daselaar, et al., 2008), and level of details (Addis, Moscovitch, et al., 2004). Our findings also provide evidence that the hippocampus works as an index of perceptual memory content during episodic memory retrieval (Moscovitch, et al., 2005; Ranganath, 2010; Teyler & Rudy, 2007).

#### 4.2. Lateralization

In controls, both the contrasts between the memory conditions and the LIWC parametric analysis indicate that regions sensitive to perceptual richness, including the hippocampus, are strongly right-lateralized. At first glance, these results are somewhat surprising in the context of a literature that has shown that both MTLs are typically involved during AM retrieval. However, they are consistent with an extensive neuropsychology literature pointing to hemispheric specialization in the temporal lobe, with the right hemisphere supporting visuo-spatial representations and memory for visual stimuli with complex configurations such as faces, spatial arrays, and scenes (Bohbot, et al., 1998; Jones-Gotman & Milner, 1978; Morris, Pickering, Abrahams, & Feigenbaum, 1996; Moscovitch & McAndrews, 2002; Nestor, Plaut, & Behrmann, 2011; Olson, Plotzker, & Ezzyat, 2007; Smith & Milner, 1989; Spiers, Maguire, & Burgess, 2001). Thus, although AM engages both hippocampi, each hippocampus may contribute preferentially to different memory dimensions or processes, and our fMRI results from healthy adults indicate that perceptually rich memory content is supported disproportionately by the right hemisphere.

Additional evidence of hemispheric specialization during AM retrieval includes the observation that right hippocampal activity is driven by ratings of mental image quality (Viard et al., 2007) and by *episodic richness*, a measure that reflects how AMs are laden with episodic details (St Jacques et al., 2012). Maguire (2001b; Spiers, Burgess, et al., 2001) has suggested that the left hippocampus might support the retrieval of event details (who did what when), while the right hippocampus might specialize in spatial memory and navigation. Kosslyn and colleagues have also shown that representations based on semantics and categorical distinctions rely preferentially on the left hemisphere of the brain, while imagery that involves very specific spatial representations relies preferentially on the right hemisphere (Kosslyn, Maljkovic, Hamilton, Horwitz, & Thompson, 1995; Kosslyn, Thompson, Sukel, & Alpert, 2005; Kosslyn et al., 1989). Similarly, Stevens and colleagues (Stevens, Kahn, Wig, & Schacter, 2012) have

shown that the left parahippocampal place area (PPA), a region that provides significant inputs into the hippocampus proper, shows repetition suppression to conceptually similar images of scenes, while the right PPA only shows repetition suppression to the exact same scene, providing evidence of form-specific visual processing in the right MTL. The same authors also reported greater functional connectivity between the right PPA and posterior cortical regions involved in perception (e.g., middle occipital gyrus), while the left PPA had greater connectivity with regions involved in abstract and conceptual processes such as the posterior inferior frontal gyrus (Stevens et al., 2012). Together with our results, these different findings are consistent with the idea that the right MTL contributes disproportionately to the integration of perceptual content during episodic memory retrieval.

At first glance, the strongly lateralized pattern we observed in the current study is difficult to reconcile with our previous reports that perceptual memory content is equally impoverished in patients with either left- or right-lateralized damage to the MTL, with no trend for group differences (St-Laurent et al., 2009, 2014). What these different findings may indicate is that the left hippocampus plays a more dominant role when searching and accessing AM, as suggested by early studies of AM retrieval that mostly revealed left-lateralized profiles of activation (Gilboa et al., 2004; Maguire, 2001a, 2001b; Spiers, Burgess, et al., 2001). On the other hand, bilateral activation is more likely to be reported when more time is given to retrieve memories, or when the memory is more emotional (Cabeza & St Jacques, 2007; Svoboda et al., 2006). We propose that the left hippocampus may be an essential node in memory access and the subsequent functional recruitment of the right hippocampus within the AM network; once recruited, the right hippocampus may then interact with posterior cortical regions that store perceptual memory content. According to this scenario, damage to either the left or the right MTL would lead to a paucity of perceptual memory content.

Although this account is speculative, experimental evidence in its favor exists in the literature: within the time course of AM retrieval, electroencephalography (EEG) indicates a shift in activity from an early left anterior component (e.g., inferior frontal gyrus and temporal pole performing search and retrieval processes) to a late right-lateralized posterior component (e.g., temporo-occipital cortex supporting sensory-perceptual episodic knowledge; Conway, Pleydell-Pearce, & Whitecross, 2001; Conway, Pleydell-Pearce, Whitecross, & Sharpe, 2003). In addition, evidence from fMRI indicates that the left anterior hippocampus interacts with frontal areas during the early “construction” (Addis, Wong, & Schacter, 2007) phase of AM retrieval when a memory is first accessed, while bilateral posterior hippocampus interacted with perceptual areas during the later “elaboration” phase during which the memory is re-experienced (McCormick et al., 2015). Right hippocampal activation has also been shown to be sustained at the moment when posterior cortical regions that included visual and auditory cortices and the precuneus became engaged, and to decline as activity ramped up in those structures during elaboration (Daselaar et al., 2008). Although these different findings suggest complementary roles for the two hippocampi during AM retrieval that are consistent with our current results, additional work is needed to understand

fully the interactions between the left and right MTL during different phases of AM retrieval in healthy and clinical populations.

As discussed, the current experimental conditions were designed to match at a conceptual level (gist), but to differ in terms of the richness of perceptual re-experiencing they elicited. According to Poppenk, Evensmoen, Moscovitch, and Nadel (2013), this experimental dissociation between gist and details is the kind of manipulation that should engage the anterior and posterior portions of the hippocampus, respectively. Using Poppenk and colleagues' recommendation that the posterior uncus serves as the demarcation between anterior and posterior hippocampus, we note that many investigators have reported how highly specific memory details and fine-grained spatial information are represented posteriorly in the hippocampus (e.g., Aly, Ranganath, & Yonelinas, 2013; Nadel, Hoescheidt, & Ryan, 2013; see Poppenk et al., 2013 for a review). Previous studies also indicate that when constructing detailed scenes (Zeidman, Mullally, & Maguire, 2015) or autobiographical memories (McCormick et al., 2015), peak activation is in the anterior hippocampus (in a region that is close to the peak activation we observed in our study). McCormick et al. (2015) further showed that this anterior hippocampal region acts as a hub that recruits anterior neocortical regions implicated in schema or gist instantiation needed for event construction, followed by posterior hippocampal and neocortical activations needed for elaboration of event details. By comparison, in our study, the patterns of hippocampal activation that reflected or were related to perceptual memory content (clips > narratives in 14 controls, correlation with LIWC measure in the clip condition in 12 controls, 12 controls > 12 mTLE within memory condition) were evident in both the anterior (most often close to the demarcation line) and posterior (in the body, not extending as far back as the tail) portion of the hippocampus. This middle region may be a point of interaction between memory details represented in posterior neocortex and more gist like-like memories or schemas represented in anterior neocortex (Robin et al., 2015).

#### 4.3. Common memory regions

Our results indicate that memory for real-life episodes and for LEs designed to mimic them both engaged similar sets of brain regions in the controls. Contrary to previous reports of minimal overlap in brain activation between autobiographical and laboratory episodic memory tasks (Gilboa, 2004; McDermott, Szpunar, & Christ, 2009), our findings confirm the prediction that laboratory tasks that mimic AM tasks or have a strong recollective component can engage the AM network successfully (Andrews-Hanna, Saxe, & Yarkoni, 2014; Burianova & Grady, 2007; Burianova, McIntosh, & Grady, 2010; Cabeza et al., 2004; Rugg et al., 2012).

More specifically, activity patterns common to our memory tasks included regions that form the default mode network (DMN; Buckner, Andrews-Hanna, & Schacter, 2008; Raichle et al., 2001) such as the angular portion of the inferior parietal lobule, the posterior cingulate cortex, the left temporal pole and lateral temporal cortex, and the bilateral MTL, including the hippocampus proper. This finding is consistent with much

replicated evidence that AM engages DMN regions (Addis, McIntosh, et al., 2004; Addis, Moscovitch, et al., 2007; Andrews-Hanna et al., 2010; Buckner & Carroll, 2007; Cabeza & St Jacques, 2007; Maguire, 2001a; Spreng, Mar, & Kim, 2009; Svoboda et al., 2006), though recent studies have pointed to a MTL-episodic subnetwork within the greater DMN (Andrews-Hanna et al., 2014; Robin et al., 2015). In addition, activated regions such as the inferior frontal gyrus, the caudate nucleus, the left hippocampus and the left lingual gyrus have been shown to form a common declarative memory network engaged during the retrieval of autobiographical, semantic and laboratory episodic memory (Burianova & Grady, 2007; Burianova et al., 2010). Altogether, our results indicate that all three of our memory conditions engaged general declarative memory retrieval processes, as well as processes more typically involved in the retrieval of real-life memory episodes.

Although our laboratory tasks engaged the AM retrieval network successfully, we also identified regions whose activation differed between AM on one hand, and clips and narratives on the other. Several dimensions distinguished AM from narratives and clips, such as recency, rehearsal, emotionality and personal relevance. This latter characteristic appeared particularly influential, as both posterior cingulate and medial prefrontal cortices, regions that are typically activated during tasks with high personal relevance (Buckner & Carroll, 2007; Cavanna & Trimble, 2006; Craik et al., 1999; Gusnard, Akbudak, Shulman, & Raichle, 2001; Kelley et al., 2002; Rabin et al., 2010; Spreng & Grady, 2010; St Jacques et al., 2011; Svoboda et al., 2006), showed greater activation during AM retrieval. The left angular gyrus, a region typically engaged during tasks of episodic recollection (Rugg & Vilberg, 2013), was also more activated during AM, which may have reflected a greater sense of recollection or a larger influx of episodic details (Leiker & Johnson, 2014; Vilberg & Rugg, 2009) in the AM task.

On the other hand, both laboratory conditions engaged the intraparietal sulcus, the middle frontal gyrus (DLPFC), the SMA/middle cingulate cortex and the posterior portion of the precuneus to a greater extent than AM. Some of these regions (IPS, posterior precuneus, SMA and DLPFC) are part of a frontoparietal “control” network, which plays a role in top-down attentional modulation (Corbetta & Shulman, 2002; Corbetta, Patel, & Shulman, 2008; Dosenbach, Fair, Cohen, Schlaggar, & Petersen, 2008; Spreng, Sepulcre, Turner, Stevens, & Schacter, 2013; Toro, Fox, & Paus, 2008). It appears that the two laboratory conditions may have required more response monitoring than AM, which is more open-ended and may engage more intuitive evaluation processes (e.g., feeling-of-rightness; Gilboa et al., 2006; Winocur & Moscovitch, 2002). Nevertheless, discrepancies between our task's conditions were subtle in comparison to the broad overlap between the whole-brain activity patterns they elicited.

## 5. Conclusion

We used a laboratory memory paradigm that successfully engaged the canonical AM retrieval network to identify a collection of posterior cortical and medial temporal regions sensitive to perceptual memory content, with the right

hippocampus among them. Although both hippocampi are known to support the retrieval of complex multi-sensory events, our results indicate that, in a healthy brain, the right hemisphere is more directly involved in the retrieval of the type of sensory details that make memories life-like. Moreover, focal damage to the right hippocampus reduces the cortical signals that reflect perceptual memory content. These findings reveal a mechanism via which hippocampal engagement leads to the subjective experience of recollection, that is, via the retrieval of perceptual memory content.

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## Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.cortex.2016.08.010>.

## REFERENCES

- Addis, D. R. (2005). *Investigating the engagement of the hippocampus and related structures during autobiographical memory retrieval in healthy individuals and temporal lobe epilepsy patients*. PhD thesis. Toronto, Canada: University of Toronto.
- Addis, D. R., Cheng, T., Roberts, R. P., & Schacter, D. L. (2011). Hippocampal contributions to the episodic simulation of specific and general future events. *Hippocampus*, 21(10), 1045–1052.
- Addis, D. R., McIntosh, A. R., Moscovitch, M., Crawley, A. P., & McAndrews, M. P. (2004). Characterizing spatial and temporal features of autobiographical memory retrieval networks: A partial least squares approach. *NeuroImage*, 23(4), 1460–1471.
- Addis, D. R., Moscovitch, M., Crawley, A. P., & McAndrews, M. P. (2004). Recollective qualities modulate hippocampal activation during autobiographical memory retrieval. *Hippocampus*, 14(6), 752–762.
- Addis, D. R., Moscovitch, M., & McAndrews, M. P. (2007). Consequences of hippocampal damage across the autobiographical memory network in left temporal lobe epilepsy. *Brain*, 130(Pt 9), 2327–2342.
- Addis, D. R., Wong, A. T., & Schacter, D. L. (2007). Remembering the past and imagining the future: Common and distinct neural substrates during event construction and elaboration. *Neuropsychologia*, 45(7), 1363–1377.

- Aly, M., Ranganath, C., & Yonelinas, A. P. (2013). Detecting changes in scenes: The hippocampus is critical for strength-based perception. *Neuron*, 78(6), 1127–1137.
- Andrews-Hanna, J. R., Reidler, J. S., Sepulcre, J., Poulin, R., & Buckner, R. L. (2010). Functional-anatomic fractionation of the brain's default network. *Neuron*, 65(4), 550–562.
- Andrews-Hanna, J. R., Saxe, R., & Yarkoni, T. (2014). Contributions of episodic retrieval and mentalizing to autobiographical thought: Evidence from functional neuroimaging, resting-state connectivity, and fMRI meta-analyses. *NeuroImage*, 91C, 324–335.
- Barnett, A. J., Park, M. T., Pipitone, J., Chakravarty, M. M., & McAndrews, M. P. (2015). Functional and structural correlates of memory in patients with mesial temporal lobe epilepsy. *Frontiers in Neurology*, 6, 103.
- Ben-Yakov, A., & Dudai, Y. (2011). Constructing realistic engrams: Poststimulus activity of hippocampus and dorsal striatum predicts subsequent episodic memory. *The Journal of Neuroscience*, 31(24), 9032–9042.
- Ben-Yakov, A., Eshel, N., & Dudai, Y. (2013). Hippocampal immediate poststimulus activity in the encoding of consecutive naturalistic episodes. *Journal of Experimental Psychology: General*, 142(4), 1255–1263.
- Ben-Yakov, A., Rubinson, M., & Dudai, Y. (2014). Shifting gears in hippocampus: Temporal dissociation between familiarity and novelty signatures in a single event. *The Journal of Neuroscience: the Official Journal of the Society for Neuroscience*, 34(39), 12973–12981.
- Bohbot, V. D., Kalina, M., Stepankova, K., Spackova, N., Petrides, M., & Nadel, L. (1998). Spatial memory deficits in patients with lesions to the right hippocampus and to the right parahippocampal cortex. *Neuropsychologia*, 36(11), 1217–1238.
- Bonnici, H. M., Chadwick, M. J., Lutti, A., Hassabis, D., Weiskopf, N., & Maguire, E. A. (2013). Detecting representations of recent and remote autobiographical memories in vmPFC and Hippocampus. *The Journal of Neuroscience: the Official Journal of the Society for Neuroscience*, 32(47), 16982–16991.
- Bonnici, H. M., Sidhu, M., Chadwick, M. J., Duncan, J. S., & Maguire, E. A. (2013). Assessing hippocampal functional reserve in temporal lobe epilepsy: A multi-voxel pattern analysis of fMRI data. *Epilepsy Research*, 105(1–2), 140–149.
- Brewer, W. F. (1986). What is autobiographical memory? In D. C. Rubin (Ed.), *Autobiographical memory* (pp. 25–49). Cambridge, UK: Cambridge University Press.
- Brewer, W. F. (1995). What is recollective memory? In D. C. Rubin (Ed.), *Remembering our past: Studies in autobiographical memory* (pp. 19–66). Cambridge, England: Cambridge University Press.
- Buchsbaum, B. R., Lemire-Rodger, S., Fang, C., & Abdi, H. (2012). The neural basis of vivid memory is patterned on perception. *Journal of Cognitive Neuroscience*, 24(9), 1867–1883.
- Buckner, R. L., Andrews-Hanna, J. R., & Schacter, D. L. (2008). The brain's default network: Anatomy, function, and relevance to disease. *Annals of the New York Academy of Sciences*, 1124, 1–38.
- Buckner, R. L., & Carroll, D. C. (2007). Self-projection and the brain. *Trends in Cognitive Sciences*, 11(2), 49–57.
- Burianova, H., & Grady, C. L. (2007). Common and unique neural activations in autobiographical, episodic, and semantic retrieval. *Journal of Cognitive Neuroscience*, 19(9), 1520–1534.
- Burianova, H., McIntosh, A. R., & Grady, C. L. (2010). A common functional brain network for autobiographical, episodic, and semantic memory retrieval. *NeuroImage*, 49(1), 865–874.
- Cabeza, R., Prince, S. E., Daselaar, S. M., Greenberg, D. L., Budde, M., Dolcos, F., et al. (2004). Brain activity during episodic retrieval of autobiographical and laboratory events: An fMRI study using a novel photo paradigm. *Journal of Cognitive Neuroscience*, 16(9), 1583–1594.
- Cabeza, R., & St Jacques, P. (2007). Functional neuroimaging of autobiographical memory. *Trends in Cognitive Sciences*, 11(5), 219–227.
- Cavanna, A. E., & Trimble, M. R. (2006). The precuneus: A review of its functional anatomy and behavioural correlates. *Brain*, 129(Pt 3), 564–583.
- Chadwick, M. J., Hassabis, D., Weiskopf, N., & Maguire, E. A. (2010). Decoding individual episodic memory traces in the human hippocampus. *Current Biology*, 20(6), 544–547.
- Conway, M. A. (2009). Episodic memories. *Neuropsychologia*, 47(11), 2305–2313.
- Conway, M. A., Pleydell-Pearce, C. W., & Whitecross, S. E. (2001). The neuroanatomy of autobiographical memory: A slow cortical potential study of autobiographical memory retrieval. *Journal of Memory and Language*, 45(3), 493–524.
- Conway, M. A., Pleydell-Pearce, C. W., Whitecross, S. E., & Sharpe, H. (2003). Neurophysiological correlates of memory for experienced and imagined events. *Neuropsychologia*, 41(3), 334–340.
- Corbetta, M., Patel, G., & Shulman, G. L. (2008). The reorienting system of the human brain: From environment to theory of mind. *Neuron*, 58(3), 306–324.
- Corbetta, M., & Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nature Reviews Neuroscience*, 3(3), 201–215.
- Craik, F. I., Moroz, T. M., Moscovitch, M., Stuss, D. T., Winocur, G., Tulving, E., et al. (1999). In search of the self: A position emission tomography study. *Psychological Science*, 10(1), 23–34.
- Daselaar, S. M., Porat, Y., Huijbers, W., & Pennartz, C. M. (2010). Modality-specific and modality-independent components of the human imagery system. *NeuroImage*, 52(2), 677–685.
- Daselaar, S. M., Rice, H. J., Greenberg, D. L., Cabeza, R., LaBar, K. S., & Rubin, D. C. (2008). The spatiotemporal dynamics of autobiographical memory: Neural correlates of recall, emotional intensity, and reliving. *Cerebral Cortex*, 18(1), 217–229.
- Diana, R. A., Yonelinas, A. P., & Ranganath, C. (2007). Imaging recollection and familiarity in the medial temporal lobe: A three-component model. *Trends in Cognitive Sciences*, 11(9), 379–386.
- Dickerson, B. C., & Eichenbaum, H. (2010). The episodic memory system: Neurocircuitry and disorders. *Neuropsychopharmacology: Official Publication of the American College of Neuropsychopharmacology*, 35(1), 86–104.
- Dickerson, B. C., Salat, D. H., Greve, D. N., Chua, E. F., Rand-Giovannetti, E., Rentz, D. M., et al. (2005). Increased hippocampal activation in mild cognitive impairment compared to normal aging and AD. *Neurology*, 65(3), 404–411.
- Dosenbach, N. U., Fair, D. A., Cohen, A. L., Schlaggar, B. L., & Petersen, S. E. (2008). A dual-networks architecture of top-down control. *Trends in Cognitive Sciences*, 12(3), 99–105.
- Epstein, R., & Kanwisher, N. (1998). A cortical representation of the local visual environment. *Nature*, 392(6676), 598–601.
- Epstein, R. A., Parker, W. E., & Feiler, A. M. (2007). Where am I now? Distinct roles for parahippocampal and retrosplenial cortices in place recognition. *The Journal of Neuroscience: the Official Journal of the Society for Neuroscience*, 27(23), 6141–6149.
- Finke, C., Bruehl, H., Duzel, E., Heekeren, H. R., & Ploner, C. J. (2013). Neural correlates of short-term memory reorganization in humans with hippocampal damage. *The Journal of Neuroscience: the Official Journal of the Society for Neuroscience*, 33(27), 11061–11069.
- Fischl, B., Salat, D. H., Busa, E., Albert, M., Dieterich, M., Haselgrove, C., et al. (2002). Whole brain segmentation: Automated labeling of neuroanatomical structures in the human brain. *Neuron*, 33(3), 341–355.
- Fischl, B., Salat, D. H., van der Kouwe, A. J., Makris, N., Segonne, F., Quinn, B. T., et al. (2004). Sequence-independent

- segmentation of magnetic resonance images. *NeuroImage*, 23(Suppl 1), S69–S84.
- Fletcher, P. C., Frith, C. D., Baker, S. C., Shallice, T., Frackowiak, R. S., & Dolan, R. J. (1995). The mind's eye—precuneus activation in memory-related imagery. *NeuroImage*, 2(3), 195–200.
- Furman, O., Mendelsohn, A., & Dudai, Y. (2012). The episodic engram transformed: Time reduces retrieval-related brain activity but correlates it with memory accuracy. *Learning & Memory*, 19(12), 575–587.
- Gilboa, A. (2004). Autobiographical and episodic memory—one and the same? Evidence from prefrontal activation in neuroimaging studies. *Neuropsychologia*, 42(10), 1336–1349.
- Gilboa, A., Alain, C., Stuss, D. T., Melo, B., Miller, S., & Moscovitch, M. (2006). Mechanisms of spontaneous confabulations: A strategic retrieval account. *Brain*, 129(Pt 6), 1399–1414.
- Gilboa, A., Winocur, G., Grady, C. L., Hevenor, S. J., & Moscovitch, M. (2004). Remembering our past: Functional neuroanatomy of recollection of recent and very remote personal events. *Cerebral Cortex*, 14(11), 1214–1225.
- Graham, K. S., Barense, M. D., & Lee, A. C. (2010). Going beyond LTM in the MTL: A synthesis of neuropsychological and neuroimaging findings on the role of the medial temporal lobe in memory and perception. *Neuropsychologia*, 48(4), 831–853.
- Grill-Spector, K., Kourtzi, Z., & Kanwisher, N. (2001). The lateral occipital complex and its role in object recognition. *Vision Research*, 41(10–11), 1409–1422.
- Gusnard, D. A., Akbudak, E., Shulman, G. L., & Raichle, M. E. (2001). Medial prefrontal cortex and self-referential mental activity: Relation to a default mode of brain function. *Proceedings of the National Academy of Sciences of the United States of America*, 98(7), 4259–4264.
- Hassabis, D., Kumaran, D., & Maguire, E. A. (2007). Using imagination to understand the neural basis of episodic memory. *The Journal of Neuroscience: the Official Journal of the Society for Neuroscience*, 27(52), 14365–14374.
- Hassabis, D., Kumaran, D., Vann, S. D., & Maguire, E. A. (2007). Patients with hippocampal amnesia cannot imagine new experiences. *Proceedings of the National Academy of Sciences of the United States of America*, 104(5), 1726–1731.
- Hassabis, D., & Maguire, E. A. (2007). Deconstructing episodic memory with construction. *Trends in Cognitive Sciences*, 11(7), 299–306.
- Hassabis, D., & Maguire, E. A. (2009). The construction system of the brain. *Philosophical Transactions of the Royal Society of London Series B Biological Sciences*, 364(1521), 1263–1271.
- Hasson, U., Furman, O., Clark, D., Dudai, Y., & Davachi, L. (2008). Enhanced intersubject correlations during movie viewing correlate with successful episodic encoding. *Neuron*, 57(3), 452–462.
- Huijbers, W., Pennartz, C. M., Rubin, D. C., & Daselaar, S. M. (2011). Imagery and retrieval of auditory and visual information: Neural correlates of successful and unsuccessful performance. *Neuropsychologia*, 49(7), 1730–1740.
- Jones-Gotman, M., & Milner, B. (1978). Right temporal-lobe contribution to image-mediated verbal learning. *Neuropsychologia*, 16(1), 61–71.
- Kanwisher, N., McDermott, J., & Chun, M. M. (1997). The fusiform face area: A module in human extrastriate cortex specialized for face perception. *The Journal of Neuroscience: the Official Journal of the Society for Neuroscience*, 17(11), 4302–4311.
- Kelley, W. M., Macrae, C. N., Wyland, C. L., Caglar, S., Inati, S., & Heatherton, T. F. (2002). Finding the self? An event-related fMRI study. *Journal of Cognitive Neuroscience*, 14(5), 785–794.
- Kosslyn, S. M., Koenig, O., Barrett, A., Cave, C. B., Tang, J., & Gabrieli, J. D. (1989). Evidence for two types of spatial representations: Hemispheric specialization for categorical and coordinate relations. *Journal of Experimental Psychology: Human Perception and Performance*, 15(4), 723–735.
- Kosslyn, S. M., Maljkovic, V., Hamilton, S. E., Horwitz, G., & Thompson, W. L. (1995). Two types of image generation: Evidence for left and right hemisphere processes. *Neuropsychologia*, 33(11), 1485–1510.
- Kosslyn, S. M., Thompson, W. L., Sukel, K. E., & Alpert, N. M. (2005). Two types of image generation: Evidence from PET. *Cognitive, Affective & Behavioral Neuroscience*, 5(1), 41–53.
- Kurby, C. A., & Zacks, J. M. (2008). Segmentation in the perception and memory of events. *Trends in Cognitive Sciences*, 12(2), 72–79.
- Lehmann, D., Pascual-Marqui, R. D., Strik, W. K., & Koenig, T. (2010). Core networks for visual-concrete and abstract thought content: A brain electric microstate analysis. *NeuroImage*, 49(1), 1073–1079.
- Leiker, E. K., & Johnson, J. D. (2014). Neural reinstatement and the amount of information recollected. *Brain Research*, 1582, 125–138.
- Levine, B., Svoboda, E., Hay, J. F., Winocur, G., & Moscovitch, M. (2002). Aging and autobiographical memory: Dissociating episodic from semantic retrieval. *Psychology and Aging*, 17(4), 677–689.
- Litman, L., Awipi, T., & Davachi, L. (2009). Category-specificity in the human medial temporal lobe cortex. *Hippocampus*, 19(3), 308–319.
- Maguire, E. A. (2001a). Neuroimaging studies of autobiographical event memory. *Philosophical Transactions of the Royal Society of London B Biological Sciences*, 356(1413), 1441–1451.
- Maguire, E. A. (2001b). Neuroimaging, memory and the human hippocampus. *Revue Neurologique (Paris)*, 157(8–9 Pt 1), 791–794.
- Maguire, E. A., & Frith, C. D. (2003). Aging affects the engagement of the hippocampus during autobiographical memory retrieval. *Brain*, 126(Pt 7), 1511–1523.
- Malach, R., Reppas, J. B., Benson, R. R., Kwong, K. K., Jiang, H., Kennedy, W. A., et al. (1995). Object-related activity revealed by functional magnetic resonance imaging in human occipital cortex. *Proceedings of the National Academy of Sciences of the United States of America*, 92(18), 8135–8139.
- McCormick, C., Protzner, A. B., Barnett, A. J., Cohn, M., Valiante, T. A., & McAndrews, M. P. (2014). Linking DMN connectivity to episodic memory capacity: What can we learn from patients with medial temporal lobe damage? *NeuroImage Clinical*, 5, 188–196.
- McCormick, C., St-Laurent, M., Ty, A., Valiante, T. A., & McAndrews, M. P. (2015). Functional and effective hippocampal-neocortical connectivity during construction and elaboration of autobiographical memory retrieval. *Cerebral Cortex*, 25(5), 1297–1305.
- McDermott, K. B., Szpunar, K. K., & Christ, S. E. (2009). Laboratory-based and autobiographical retrieval tasks differ substantially in their neural substrates. *Neuropsychologia*, 47(11), 2290–2298.
- Morris, R. G., Pickering, A., Abrahams, S., & Feigenbaum, J. D. (1996). Space and the hippocampal formation in humans. *Brain Research Bulletin*, 40(5–6), 487–490.
- Moscovitch, D. A., & McAndrews, M. P. (2002). Material-specific deficits in “remembering” in patients with unilateral temporal lobe epilepsy and excisions. *Neuropsychologia*, 40(8), 1335–1342.
- Moscovitch, M., Rosenbaum, R. S., Gilboa, A., Addis, D. R., Westmacott, R., Grady, C., et al. (2005). Functional neuroanatomy of remote episodic, semantic and spatial memory: A unified account based on multiple trace theory. *Journal of Anatomy*, 207(1), 35–66.
- Nadel, L., Campbell, J., & Ryan, L. (2007). Autobiographical memory retrieval and hippocampal activation as a function of repetition and the passage of time. *Neural Plasticity*, 2007, 90472.

- Nadel, L., Hoescheidt, S., & Ryan, L. R. (2013). Spatial cognition and the hippocampus: The anterior-posterior axis. *Journal of Cognitive Neuroscience*, 25(1), 22–28.
- Nadel, L., & Moscovitch, M. (1997). Memory consolidation, retrograde amnesia and the hippocampal complex. *Current Opinion in Neurobiology*, 7(2), 217–227.
- Nestor, A., Plaut, D. C., & Behrmann, M. (2011). Unraveling the distributed neural code of facial identity through spatiotemporal pattern analysis. *Proceedings of the National Academy of Sciences of the United States of America*, 108(24), 9998–10003.
- Nichols, T., Brett, M., Andersson, J., Wager, T., & Poline, J. B. (2005). Valid conjunction inference with the minimum statistic. *NeuroImage*, 25(3), 653–660.
- Noulhiane, M., Piolino, P., Hasboun, D., Clemenceau, S., Baulac, M., & Samson, S. (2008). Autonoetic consciousness in autobiographical memories after medial temporal lobe resection. *Behavioural Neurology*, 19(1–2), 19–22.
- Olson, I. R., Plotzker, A., & Ezzyat, Y. (2007). The enigmatic temporal pole: A review of findings on social and emotional processing. *Brain*, 130(Pt 7), 1718–1731.
- Pardoe, H. R., Pell, G. S., Abbott, D. F., & Jackson, G. D. (2009). Hippocampal volume assessment in temporal lobe epilepsy: How good is automated segmentation? *Epilepsia*, 50(12), 2586–2592.
- Pennebaker, J. W., Chung, C. K., Ireland, M., Gonzales, A., & Booth, R. J. (2007). *The development and psychometric properties of LIWC2007*. Austin, TX: Software Manual.
- Piolino, P., Desgranges, B., & Eustache, F. (2009). Episodic autobiographical memories over the course of time: Cognitive, neuropsychological and neuroimaging findings. *Neuropsychologia*, 47(11), 2314–2329.
- Poppenk, J., Evensmoen, H. R., Moscovitch, M., & Nadel, L. (2013). Long-axis specialization of the human hippocampus. *Trends in Cognitive Sciences*, 17(5), 230–240.
- Rabin, J. S., Gilboa, A., Stuss, D. T., Mar, R. A., & Rosenbaum, R. S. (2010). Common and unique neural correlates of autobiographical memory and theory of mind. *Journal of Cognitive Neuroscience*, 22(6), 1095–1111.
- Raichle, M. E., MacLeod, A. M., Snyder, A. Z., Powers, W. J., Gusnard, D. A., & Shulman, G. L. (2001). A default mode of brain function. *Proceedings of the National Academy of Sciences of the United States of America*, 98(2), 676–682.
- Ranganath, C. (2010). A unified framework for the functional organization of the medial temporal lobes and the phenomenology of episodic memory. *Hippocampus*, 20(11), 1263–1290.
- Robin, J., Hirshhorn, M., Rosenbaum, R. S., Winocur, G., Moscovitch, M., & Grady, C. L. (2015). Functional connectivity of hippocampal and prefrontal networks during episodic and spatial memory based on real-world environments. *Hippocampus*, 25(1), 81–93.
- Rubin, D. C., Schrauf, R. W., & Greenberg, D. L. (2003). Belief and recollection of autobiographical memories. *Memory & Cognition*, 31(6), 887–901.
- Rugg, M. D., & Vilberg, K. L. (2013). Brain networks underlying episodic memory retrieval. *Current Opinion in Neurobiology*, 23(2), 255–260.
- Rugg, M. D., Vilberg, K. L., Mattson, J. T., Yu, S. S., Johnson, J. D., & Suzuki, M. (2012). Item memory, context memory and the hippocampus: fMRI evidence. *Neuropsychologia*, 50(13), 3070–3079.
- Schacter, D. L., Addis, D. R., & Buckner, R. L. (2007). Remembering the past to imagine the future: The prospective brain. *Nature Reviews Neuroscience*, 8(9), 657–661.
- Schmidt, M. (2010). *RAVLT: A handbook* (third printing). Los Angeles, CA: Western Psychological Services.
- Sheldon, S., & Levine, B. (2013). Same as it ever was: Vividness modulates the similarities and differences between the neural networks that support retrieving remote and recent autobiographical memories. *NeuroImage*, 83, 880–891.
- Smith, M. L., & Milner, B. (1989). Right hippocampal impairment in the recall of spatial location: Encoding deficit or rapid forgetting? *Neuropsychologia*, 27(1), 71–81.
- Sperling, R. A., Dickerson, B. C., Pihlajamaki, M., Vannini, P., LaViolette, P. S., Vitolo, O. V., et al. (2010). Functional alterations in memory networks in early Alzheimer's disease. *Neuromolecular Medicine*, 12(1), 27–43.
- Spiers, H. J., Burgess, N., Maguire, E. A., Baxendale, S. A., Hartley, T., Thompson, P. J., et al. (2001). Unilateral temporal lobectomy patients show lateralized topographical and episodic memory deficits in a virtual town. *Brain*, 124(Pt 12), 2476–2489.
- Spiers, H. J., Maguire, E. A., & Burgess, N. (2001). Hippocampal amnesia. *Neurocase*, 7(5), 357–382.
- Spreen, O., & Strauss, E. (1991). *A compendium of neuropsychological tests: Administration, norms and commentary*. New York: Oxford University Press.
- Spreng, R. N., & Grady, C. L. (2010). Patterns of brain activity supporting autobiographical memory, prospection, and theory of mind, and their relationship to the default mode network. *Journal of Cognitive Neuroscience*, 22(6), 1112–1123.
- Spreng, R. N., Mar, R. A., & Kim, A. S. (2009). The common neural basis of autobiographical memory, prospection, navigation, theory of mind, and the default mode: A quantitative meta-analysis. *Journal of Cognitive Neuroscience*, 21(3), 489–510.
- Spreng, R. N., Sepulcre, J., Turner, G. R., Stevens, W. D., & Schacter, D. L. (2013). Intrinsic architecture underlying the relations among the default, dorsal attention, and frontoparietal control networks of the human brain. *Journal of Cognitive Neuroscience*, 25(1), 74–86.
- St Jacques, P. L., Conway, M. A., Lowder, M. W., & Cabeza, R. (2011). Watching my mind unfold versus yours: An fMRI study using a novel camera technology to examine neural differences in self-projection of self versus other perspectives. *Journal of Cognitive Neuroscience*, 23(6), 1275–1284.
- St Jacques, P. L., Rubin, D. C., & Cabeza, R. (2012). Age-related effects on the neural correlates of autobiographical memory retrieval. *Neurobiology of Aging*, 33(7), 1298–1310.
- St-Laurent, M., Moscovitch, M., Jadd, R., & McAndrews, M. P. (2014). The perceptual richness of complex memory episodes is compromised by medial temporal lobe damage. *Hippocampus*, 24(5), 560–576.
- St-Laurent, M., Moscovitch, M., Levine, B., & McAndrews, M. P. (2009). Determinants of autobiographical memory in patients with unilateral temporal lobe epilepsy or excisions. *Neuropsychologia*, 47(11), 2211–2221.
- Stark, C. E., & Squire, L. R. (2001). When zero is not zero: The problem of ambiguous baseline conditions in fMRI. *Proceedings of the National Academy of Sciences of the United States of America*, 98(22), 12760–12766.
- Stevens, W. D., Kahn, I., Wig, G. S., & Schacter, D. L. (2012). Hemispheric asymmetry of visual scene processing in the human brain: Evidence from repetition priming and intrinsic activity. *Cerebral Cortex*, 22(8), 1935–1949.
- Strauss, E., Sherman, E. M. S., & Spreen, O. (2006). *A compendium of neuropsychological tests: Administration, norms, and commentary* (3rd ed.). New York: Oxford University Press.
- Svoboda, E., McKinnon, M. C., & Levine, B. (2006). The functional neuroanatomy of autobiographical memory: A meta-analysis. *Neuropsychologia*, 44(12), 2189–2208.
- Swallow, K. M., Barch, D. M., Head, D., Maley, C. J., Holder, D., & Zacks, J. M. (2011). Changes in events alter how people remember recent information. *Journal of Cognitive Neuroscience*, 23(5), 1052–1064.

- Teyler, T. J., & Rudy, J. W. (2007). The hippocampal indexing theory and episodic memory: Updating the index. *Hippocampus*, 17(12), 1158–1169.
- Toro, R., Fox, P. T., & Paus, T. (2008). Functional coactivation map of the human brain. *Cerebral Cortex*, 18(11), 2553–2559.
- Tulving, E. (1985). Memory and consciousness. *Canadian Psychology*, 26(1), 1–12.
- Tulving, E. (2002). Episodic memory: From mind to brain. *Annual Review of Psychology*, 53, 1–25.
- Vann, S. D., Aggleton, J. P., & Maguire, E. A. (2009). What does the retrosplenial cortex do? *Nature Reviews Neuroscience*, 10(11), 792–802.
- Viard, A., Desgranges, B., Eustache, F., & Piolino, P. (2012). Factors affecting medial temporal lobe engagement for past and future episodic events: An ALE meta-analysis of neuroimaging studies. *Brain and Cognition*, 80(1), 111–125.
- Viard, A., Piolino, P., Desgranges, B., Chetelat, G., Lebreton, K., Landeau, B., et al. (2007). Hippocampal activation for autobiographical memories over the entire lifetime in healthy aged subjects: An fMRI study. *Cerebral Cortex*, 17(10), 2453–2467.
- Vilberg, K. L., & Rugg, M. D. (2009). Left parietal cortex is modulated by amount of recollected verbal information. *NeuroReport*, 20(14), 1295–1299.
- Warrington, E. K. (1984). *Recognition memory test: Manual*. Berkshire, UK: NFER-Nelson.
- Wechsler, D. (1999). *Wechsler Abbreviated Scale of Intelligence*. San Antonio, TX.: The Psychological Corporation.
- Westmacott, R., Silver, F. L., & McAndrews, M. P. (2008). Understanding medial temporal activation in memory tasks: Evidence from fMRI of encoding and recognition in a case of transient global amnesia. *Hippocampus*, 18(3), 317–325.
- Whitfield-Gabrieli, S., & Mozes, S. (2010). *Artifact detection Tools*. Retrieved from [http://www.nitrc.org/projects/artifact\\_detect](http://www.nitrc.org/projects/artifact_detect).
- Winocur, G., & Moscovitch, M. (2002). The frontal cortex and working with memory. In D. T. S. R. T. Knight (Ed.), *The frontal lobes*. Oxford: Oxford University Press.
- Winocur, G., & Moscovitch, M. (2011). Memory transformation and systems consolidation. *Journal of the International Neuropsychological Society*, 17(5), 766–780.
- Winocur, G., Moscovitch, M., & Bontempi, B. (2010). Memory formation and long-term retention in humans and animals: Convergence towards a transformation account of hippocampal-neocortical interactions. *Neuropsychologia*, 48(8), 2339–2356.
- Yonelinas, A. P. (2013). The hippocampus supports high-resolution binding in the service of perception, working memory and long-term memory. *Behavioural Brain Research*, 254, 34–44.
- Zeidman, P., Mullally, S. L., & Maguire, E. A. (2015). Constructing, perceiving, and maintaining scenes: Hippocampal activity and connectivity. *Cerebral Cortex*, 25(10), 3836–3855.