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Episodic memory processes mediated by the medial temporal lobes contribute to open-ended problem solving

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ABSTRACT

The present study investigated the contribution of episodic memory processes mediated by the medial temporal lobes to solving open-ended problems: problems for which standard solutions or set procedures for arriving at solutions do not exist. Patients with unilateral temporal lobe epilepsy and excisions (TLE), older adults and control participants were asked to describe detailed solutions to various open-ended, social scenarios. TLE patients and older adults, both having deficits in episodic memory, provided fewer steps *relevant* to the given solution than their comparison group. Segmenting the descriptions into details using the methods of the Autobiographical Interview, we also found that patients with TLE and older adults provided fewer *internal* (episodic) details but a similar number of *external* (semantic) details compared to their control group. These findings are the first to demonstrate that processes underlying episodic memory, in particular those enabling the retrieval of experiential detail and episodic simulation may contribute to open-ended problem solving. Given that we examined groups with medial temporal lobe lesions and known episodic memory dysfunction, these results further suggest that the negative consequences of episodic memory loss resulting from damage to or deterioration of the medial temporal lobes extend beyond that of memory to include other domains, such as problem solving.

Episodic memory processes allow one to recollect past events, deal with present concerns, and imagine future events. We know a great deal about the psychological processes and neural mechanisms underlying episodic memory (e.g., Eichenbaum, Otto, & Cohen, 1992; Squire, Wixted, & Clark, 2007), but considerably less about the uses to which these episodic memory processes are put in everyday life (but see Pillemer, 2003). This matter is particularly relevant when evaluating the implications of memory loss following brain injury or deterioration for daily activities because it suggests that people with such deficits will also have impairments in areas outside of memory. In this paper, we examine the relation between episodic memory processes and problem solving. We propose that for problems that are not well-defined (open-ended problems which do not have a set path, rule or algorithm to a solution), psychological processes and the underlying neural structures associated with recalling details of past events can help develop effective solutions. Because the medial temporal lobes (MTL) and the hippocampus specifically have been implicated as crucial for recalling the past and imagining the future (Hassabis, Kumaran, Vann, & Maguire, 2007; Schacter, Addis, & Buckner, 2007), this paper also assesses whether MTL-dependent processes are involved in creating solutions for open-ended problems. To do so, we investigated patients with temporal lobe epilepsy or excisions (TLE) and healthy older adults both of whom have episodic memory dysfunction associated, respectively, with medial temporal lobe lesions or deterioration.

Considerable evidence has demonstrated that the MTLs are the hub of the episodic memory neural network. According to the Component Process Model and the Multiple Trace Theory, the MTLs construct a single, informationally rich memory trace from random co-occurring elements of consciously experienced events (Moscovitch, 1992, 2008; see also Eichenbaum, Yonelinas, & Ranganath, 2007). Detailed recall or re-experiencing of these events is thought to be dependent on the hippocampus and related MTL structures, irrespective of the time since acquisition (Nadel & Moscovitch, 1997). Importantly, the MTL-based processes underlying detailed recollection also allow for the flexible recombination of elements from different experiences, which can be used to construct novel vivid scenes and scenarios (Addis, Wong, & Schacter, 2007; Hassabis et al., 2007; Rosenbaum, Gilboa, Levine, Winocur, & Moscovitch, 2009). Functional neuroimaging studies have shown that autobiographical memory retrieval and imagining future events activate

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a common neural network that includes medial temporal regions (Addis, Moscovitch, & McAndrews, 2007; Addis, Wong, et al., 2007; Szpunar, Watson, & McDermott, 2007). Lasion studies have found that patients with medial temporal damage provide less detailed descriptions of remote personal memories (Viskontas, McAndrews, & Moscovitch, 2000) and of imagined events (Hassabis et al., 2007) than do healthy controls. Also, in comparison with younger adults, older adults typically are poorer at detailed recollection (Levine, Svoboda, Hay, Winocur, & Moscovitch, 2002) and event stimulation (Addis, Wong, & Schacter, 2008), which is likely related to hippocampal deterioration associated with aging (Driscoll et al., 2003). Together, these findings and formulations form the basis of the hypothesis that detailed remembering, as supported by the episodic memory system, can contribute to *event simulation*. That is, the very same processes that are used to recombine elements of events to *reconstruct* the past can also be used to *construct* novel scenes, scenarios and future events (Hassabis & Maguire, 2009; Schacter & Addis, 2007; Suddendorf & Corballis, 1997).

We suggest that these event simulation processes may also be used to solve ill-defined, or open-ended, problems by allowing one to simulate possible scenarios to determine the appropriate solution and/or solution paths. Unlike well-defined problems which typically have a single solution that can be reached by applying rules, algorithms, or general scripts, open-ended problems have multiple possible solutions for which there is no specific script or solution path that can be applied (Schraw, Dunkle, & Bendixen, 2006; Williams et al., 2006). Consequently, procedures for solving open-ended problems cannot be stored and retrieved from semantic memory making it likely that solutions to such problems would rely on an event simulation strategy. Supportive evidence for this hypothesis comes from studies that have shown that groups with diminished episodic memory retrieval, such as adults who are depressed (Goddard, Dritschel, & Burton, 1996) and adults who have attempted suicide (Evans, Williams, O'Loughlin, & Howells, 1992; Sidley, Whitaker, Calam, & Wells, 1997), have poor social problem solving skills, as measured by a means-end social problem solving test. These poor problem solving skills relate to their tendency to access over-general autobiographical information rather than specific, context-dependent detailed memories that are the hallmark of recollection (Williams et al., 1996, 2006). Whether this tendency to retrieve over-general autobiographical memory is related to prefrontal or medial temporal underactivity associated in depression is still not clear.

To the best of our knowledge, no study has thoroughly examined the relation between the integrity of recollective processes and the richness of event simulation mediated by a network of brain regions that includes the MTLs in relation to effectiveness in solving open-ended problems. The present investigation examined this by looking at the performance of two cohorts with known difficulties in episodic recollection and/or event simulation processes, individuals with unilateral temporal lobe epilepsy or excisions (TLE) and healthy older adults on a test of open-ended social problem solving. We predicted that the richness of event simulation as measured by the amount of detail specific to an event would correlate with problem solving effectiveness, and that overall performance would be diminished in older adults and TLE patients compared to matched control participants.

Patients with TLE are impaired at tasks that involve episodic memory, particularly recollecting autobiographical memories (Addis, Moscovitch, et al., 2007; St-Laurent, Mosovitch, Levine, & McAndrews, 2009; Viskontas et al., 2000), but they still have normal levels of intellectual functioning and generally intact performance on tests of executive functioning. Also, there is no appreciable difference in autobiographical memory between patients with medial temporal dysfunction who are awaiting surgery and those who have undergone temporal-lobe excisions that include portions of the lateral temporal neocortex in addition to the medial structures (St-Laurent et al., 2009; Viskontas et al., 2000). Thus, it is likely that any impairment on a problem solving measure is linked to the episodic memory deficits associated with TLE.

We also tested older adults because their deficient autobiographical, episodic memory (Levine et al., 2002), which is associated with medial temporal deterioration (Driscoll et al., 2003), predicts that they would show similar, though milder, problem solving deficits than TLE patients, despite having more life-experience than younger adults. Testing older adults also enabled us to eliminate non-cognitive factors associated with TLE (e.g., effects of seizures and anticonvulsant medication, other mental health issues such as depression and anxiety that some TLE patients may have) that may have contributed to deficient performance.

All participants were administered a test of open-ended social problem solving, the Means-Ends Problem Solving Test (MEPS; Platt & Spivack, 1975). In this test, participants are given the beginnings and ends of ten vignettes that each contain a social problem (e.g., Beginning: moving to a new neighborhood and wishing to make new friends – End: Becoming friends with people in the neighborhood). For each problem, they are asked to describe the middle of the story, that is, to provide the steps necessary to solve the problem. Importantly, the participants are asked to generate ideal solutions to connect the beginning and the end of the stories. They are not to provide any story, but one that effectively connects the problem to the solution (Goddard et al., 1996).

To measure problem solving effectiveness, descriptions were scored according to a method that is standardized for MEPS. The number of steps (means) *relevant* to the given solutions (i.e., end of the vignettes) as well as the total number of steps (means that included both *relevant* and *irrelevant* solutions) was recorded. To characterize the richness of details in the descriptions of the middle of the story (solution path), we used a scoring technique that was initially developed to assess autobiographical memory (The Autobiographical Interview; Levine et al., 2002). This method categorizes details present in scenarios as either *internal*, in that they are specific to the event and likely derived from episodic memory, or *external*, in that they are not specific to the event, and likely derived from semantic memory. Using this scoring procedure in the past, investigators have found a paucity of internal, but not external, details in populations with episodic memory deficits compared to control participants in their descriptions of autobiographical memories of past events (Addis, Moscovitch, et al., 2007; Levine et al., 2002; St-Laurent et al., 2009). Also, investigators have found that poorer episodic memory leads to the generation of fewer internal details on non-mnemonic simulation-based tasks, such as imagining possible future events (e.g., Addis et al., 2008; Rosenbaum et al., 2009). In all, this supports the working hypothesis that processes mediating episodic memory are related to the generation of internal details on tasks such as the MEPS and the prediction that the number of internal details will correlate with the effectiveness of solutions on the MEPS. These scores in turn, will be related to performance on tests of episodic memory that are sensitive to the integrity of the MTL.

Older adults were also administered a battery of neuropsychological tests that examined their executive functioning and memory functioning, as well as a standard version of the Autobiographical Interview (Levine et al., 2002) that assesses past event recollection and which is sensitive to hippocampal integrity. We administered these tests because in older adults, unlike in patients with TLE, episodic memory deficits often appear alongside executive function deficits. If performance on the MEPS correlated with performance on tests of episodic memory, but not of executive function, this would allow us to rule out general, age-related cognitive deterioration as an explanation for their poorer problem solving ability.

We expected that individuals with episodic memory impairment would also be impaired at providing detailed, effective solution scenarios for open-ended problems. Specifically, we predicted that patients with TLE and older adults would provide fewer *relevant* solution steps and fewer *internal* details when describing solution paths than their comparison group. Most importantly, for all participants, the number of *relevant* solution steps provided was expected to correlate with *internal*, event-specific details, consistent with the hypothesis that the richness of event simulation is related to solution efficacy.

1. Methods and materials

1.1. Experiment 1a: patients with temporal lobe epilepsy and control participants

1.1.1. Participants

Fifteen patients with temporal lobe epilepsy (5 male) with a mean age of 42.7 (SD = 9.1) and a mean of 14.9 years of education (SD = 2.5: Table 1), and fifteen matched control participants (4 male) with a mean age of 43.8 (SD = 9.2) and 15.7 years of education (SD = 2.2) participated in this study. All participants gave their informed consent in accordance with the research ethics board of the University Health Network in Toronto. Of the fifteen patients with epilepsy, seven had seizures originating in the left temporal lobe (3) or had a temporal lobe excision on the left side (4), and eight had seizures originating in the right temporal lobe (2) or had a temporal lobe excision on the right side (6). All patients awaiting surgery had mesial temporal sclerosis evident on MRI; the surgical excisions invariably included the amygdala, hippocampus, and anterior parahippocampal gyrus and most included a portion (typically less than 4 cm) of neorcortical resection in the middle and inferior temporal gyri. Given the sample size, we did not differentiate between patients with left and right TLE or between those with and without surgery. In fact, those factors have been shown to be irrelevant to the degree of autobiographical memory deficit in our previous studies (St-Laurent et al., 2009; Viskontas et al., 2000). All of the patients were recruited through the Epilepsy Program at the Toronto Western Hospital.

The control participants were recruited through on-line advertisements and were matched to patients for age and years of education. One control participant was removed from the analysis because of a psychological illness that was only disclosed after the testing session was complete. The remaining participants were all free from psychiatric disorders and English was their primary language. All participants received an honorarium for their participation.

1.1.2. Materials and scoring

The Means End Problem Solving (MEPS) test is a standardized test composed of ten vignettes, each consisting of a social problem (e.g., moving to a new neighborhood, ending a relationship; see Fig. 1 a for example vingettes). The participants were given the beginning of the problem (*problem state*) and the end of the problem (*problem resolution*) and were asked to describe out loud, in detail, an effective middle part of the story, namely, how to solve the problem. The problem state and resolution was always in front of the participants as they described the solution path. Participants were given as much time as they needed to describe their solutions fully. Also, a general probe was given after each solution was described (*Can you think of anything else you would add to this story?*) to ensure that the participants did not leave out pertinent details and to ensure that the oral responses were not being cut short for reasons other than the unavailability of more means/details. General probing also makes the test more comparable to the Autobiographical Interview.

All responses were electronically recorded and later transcribed for scoring. The responses were scored first according to the standardized method described in the MEPS manual (see Fig. 1b for example solutions scored for means). We tallied the number of means, or steps, given to move from the problem state to the solution. Each mean was classified as either a *relevant mean*, a step that moves the individual closer to the solution state, an *irrelevant mean*, a step that does not direct the individual to the desired solution but is within the context of the problem, or a *no mean*, a step that does not push the individual towards the goal state, a step described vaguely, or judgment statements. For example, for a vignette describing the problem of having an argument with a significant other and wanting things to be better with the significant other, an *relevant mean* may be to discuss relationship issues with the partner, a *irrelevant mean* may be to start relationships with other people and a *no mean* would be to decide that the relationship wasn't so good after all. *Total mean scores* results from summing the number of means in each category across all ten stories.

The responses were also scored according to procedures derived from the Autobiographical Interview (Levine et al., 2002); see Fig. 1b for examples of scoring such details on the MEPS. The Autobiographical Interview is a method used to quantify details from recollections of past events. This method categorizes details based on internal (episodic) and external (non-episodic) details and can give a measure of the level of autobiographical remembering. Responses are first segmented in events, which refer to any piece of information or detail that conveys information regarding an observation, fact, a thought or judgment. These segments are then categorized as either *internal* or *external. Internal details* are those that pertain to the story specifically and convey information that is isolated to the event described. In case of the MEPS, this relates to details that pertain to events that are isolated to the unfolding story, such as describing a location visited (e.g., building color) during the solution story. In the context of autobiographical memory tasks, these types of details are used as a measure of episodic memory processes. We hypothesize that in populations with episodic memory deficits fewer such details will be generated on the MEPS task. In contrast, on typical autobiographical tasks, *external details* are those that are not part of the main event or specific to it, such as factual information or judgment statements. In terms of the MEPS, external details are also those details that are not isolated to the context of the solution story. Given that in autobiographical memory tasks these types of details are thought to reflect retrieval mainly from semantic memory or other non-episodic, non-specific sources, we hypothesize that the number of these details will not be compromised in populations with episodic memory impairments. For each event, the number of internal and external details was tallied. Internal and external detail total scores represent the sum of all stories' internal and external details, respectively, across all ten stories.

As a note, means and details, and particularly relevant means and internal details were used to capture different aspects of problem solving. While relevant means capture efficiency of problem solving, internal details capture the richness of event simulation. In principle, such aspects of problem solving can be dissociated from one another. That is, it is possible but perhaps unlikely, to provide an efficient solution with few internal details or an inefficient solution with many internal details.

Two raters scored the MEPS with the principal rater blind to group membership. Inter-rater reliability for the number of means and the number of details was based on a series of stories, randomly chosen from different participants, that was scored by the two raters. The reliability was found to be high ($r = 0.98$, $r = 0.87$, $r = 0.96$ for internal details, external details, and means, respectively).

Scores on standard neuropsychological tests were extracted from the clinical charts of patients with TLE (see Table 1).

Table 1
Average scores for patients with temporal lobe epilepsy or excisions on neuropsychological measures. Standard deviations are in parentheses.

WASI Full Scale IQ	100.1 (9.4)
Rey Auditory Verbal Learning (RAVLT)	
Delay (maximum = 15)	7.0 (1.9)
Phonemic (FAS) fluency	37.4 (6.9)
Category fluency (animal, vegetable, fruit – 60 s each)	37.2 (9.8)

1.2. Experiment 1b: younger and older adults

1.2.1. Participants

The participants in this experiment were fifteen younger adults (mean age = 22.9 years, SD = 4.1) and fifteen older adults (mean age = 75.7 years, SD = 5.2) with 15.5 (SD = 1.3) and 15.3 (SD = 3.4) years of education, respectively. Four of the younger adults and three of the older adults were male. All had normal or corrected to normal vision, were free from neurological or psychiatric illness, and English was their primary language. The younger adults were undergraduate students at the University of Toronto and the older adults were volunteers from the community. All participants received an honorarium for their participation.

1.2.2. Materials, procedures, and scoring

The same MEPS test was administered in this experiment as it was in Experiment1a; however, in this experiment, participants were asked to write their responses. We chose this response method because it diminished the involvement of the experimenter which reduced any differential effect that experimenter characteristics (viz. age) may have on younger and older adults (Beaman, Pushkar, Etezadi, Bye, & Conway, 2006). The instructions were always in front of the participants as well the problem they were working on at that moment, thereby minimizing the effects of long-term memory for instructions or story as a contributing factor.

Unlike Experiment 1a, there was no probing after the solutions were described because the written responses made it difficult to insert it. Because probing has been shown to benefit younger adults more than older adults on tests similar to the MEPS (e.g., Levine et al., 2002), any differences that were found favouring the younger adults would likely only have been exaggerated with probing. To keep raters blind to the age of the participant, the written responses were re-typed before scoring to eliminate any clues based on handwriting. The average time to complete the study was roughly 2 h for younger adults and 2.5 h for older adults. Scoring was conducted as described in Experiment 1a.

1.2.2.1. Autobiographical Interview. Older adults were also given a version of the Autobiographical Interview in an additional testing session. In this task, participants were asked to recall five events from five different time periods: early childhood (early childhood to age 11), adolescent–teenage years (ages 11–17), early adulthood (ages 18–35), middle age (35–55), and the previous year. Each event had to be one that was contextually bound and temporally bound (i.e., episodic) in which the participant was an active participant, not one in which he or she was simply a

- Mrs. A was listening to the people speak at a local meeting about how to make things better in her neighborhood. She wanted to say something important and have a chance to be a leader too. The story ends with her being elected leader and presenting a speech.
- Mrs. P came home after shopping and found that she had lost her watch. She was very upset about it. The story ends with Mrs. P. finding her watch and feeling good about it.
- C. had just moved in that day to a new neighborhood and didn't know anyone. C. wanted to have friends in this new neighborhood. The story ends with C. having many good friends and feeling at home in the neighborhood. You begin the story with C. in her room, unpacking boxes.

b

PROBLEM: *Mrs. P came home after shopping and found that she had lost her watch. She was very upset about it. The story ends with Mrs. P. finding her watch and feeling good about it.*

SOLUTION: What had I done from the time I got out of car, going into store, shopping and then coming back? ***[internal – thought/emotion]*** So taking every move that I had made, the time I shut the door of a car, I looked in the car ***[internal –event]*** to make sure I did not take off watch while in the car ***[internal – though/emotion]***, and then when I had walked to the store from the car ***[internal –event]*** to ensure that it did not fall off the wrist ***[internal –thought/emotion]***, so I looked around the parking lot ***[internal -place]***, as I was walking through and then once I went to check the cart that I was pushing while shopping ***[internal-event]*** and then checked all the aisles ***[internal –place]***, that I had walked through, and to the point where I had to pick up medication ***[internal –place]***, as well when I was standing in ***line [internal-place]*** to pay for my product ***[internal –event]***. So, I asked any specific individual who I had seen again from the first time I was in ***[internal –event]***, and also the most obvious step that I had taken once going back into the store was to ask key employees if a watch had been tuned in ***[internal –event]***, So, when she had contacted the employee, the employee had went and brought Mrs. P to the lost and found ***[internal –event]***, where any lost items are turned in ***[external-semantic]***, which is where she had the opportunity to look within the lost and found ***[internal –event]***, and realize her watch was turned in ***[internal –event]***. She felt very good about it because it was very sentimental gift ***[external – semantic]*** given to her for her 50 birthday ***-[external-event * 2]***.

MEANS:
Initial introspection – Relevant Mean
Check specific locations - Relevant Mean.
Ask people if they've seen watch -- Relevant Mean.
Look in lost and found –Relevant Mean

PROBLEM: *Jill is having trouble getting along with the foreman or her boss at her job. Jill is very unhappy about this. The story ends with Jill's foreman/boss liking her.*

SOLUTION: Since she is not getting along with the foreman maybe she can ask about his family ***[internal-event]***. She can melt the negativity and get on his positive side ***[external-semantic]***, I mean who doesn't love their family especially if you have kids ***[external-semantic]***. She could take an interest in her **[internal-event]** if she could break the ice. Next thing you know they strike up a conversation ***[internal-event]***. I mean once she's melted the ice ***[external-repetition]*** She talks to her in a friendly manner ***[internal-event]*** And next thing you know there are getting along great.

MEANS:
Talk to foreman - Relevant Mean
They make up –vague –No Mean

Fig. 1. (a) Some vignettes from the Means-End Problem Solving (MEPS) task (Platt & Spivack, 1975). (b) Sample responses from a healthy control participant (top) and a patient with TLE (bottom) scored according to the MEPS protocol and the Autobiographical Interview scoring technique, adapted for the MEPS.

an observer. The participant was required to recall and describe these events in as much detail as possible. To keep these descriptions as similar to the MEPS as possible, we asked participants to write down their descriptions that were later retyped for scoring. No time limit was given.

1.2.2.2. Neuropsychological tests. Older adults were also given a battery of neuropsychological tests based on those given to older adults in Addis et al. (2008). The Mini-mental status exam (MMSE) was given to assess the cognitive state of the older adults. Recall scores from the Verbal Paired Associates I (VPA) subscale and the VPA II subscale of the Wechsler Memory Scale – Third Edition was given to measure relational memory (Lezak, 1995). The choice to include this test was based upon the positive correlation between VPA and event simulation reported by Addis et al. (2008). Category fluency (name as many animals within 90 s) was given as a measure of both temporal and executive functioning (Newcombe, 1969). In addition, tests sensitive to some aspects of executive functioning that are differentially affected by aging were administered. To this end, the Digit Span Backwards subscale from the Wechsler Adult Intelligence Scale–Third Edition, a test that recruits central executive resources and is affected by age (Hester, Kinsella, & Ong, 2004) as well as phonemic fluency, a test that is strongly related to inferior frontal gyrus functioning but is less affected by age (Brickman et al., 2005) were used (Lezak, 1995). This second session, involving recollection of past memories and standardized neuropsychological tests, lasted approximately two hours. The purpose of this second session was to dissociate the effect of episodic memory impairment from executive functioning, whether those aspects were impaired with age (backward digit span) or relatively preserved (phonemic fluency); thus, only the older adults were administered these tests in addition to the MEPS.

2. Results

2.1. Experiment 1a: temporal lobe epilepsy

Patients with temporal lobe epilepsy (TLE) provided the same number of *total* means as control participants (F (1, 27) = 3.076, p = 0.091, η^2 = 0.10). A repeated measures ANOVA with mean type (relevant and irrelevant/no means) as a within-subject factor and group (TLE or control) as a between-subject factor revealed a significant interaction, F(1, 27) = 26.842, p < 0.001. A subsequent analysis revealed that TLE patients generated fewer *relevant* means when compared to the matched controls (F (1, 27) = 44.225, p < 0.001, η^2 = 0.62; Fig. 2a). Moreover, when we examined the proportion of *relevant* to *total* means, we still found that the patients with TLE provided a lower proportion than the matched controls (0.62 (SD = 0.14) and 0.76 (SD = 0.09), respectively; F (1, 27) = 10.890, p = 0.003, η^2 = 0.28).

When the solutions were scored using the Autobiographical Interview scoring technique, there was a significant interaction between detail type (internal and external) and group, F (1, 27) = 26.255, p < 0.001. Patients with TLE provided fewer *internal* details (episodically-specific details) than did the controls (F (1, 27) = 16.305, p < 0.001, η^2 = 0.38; Fig. 2b) but provided the same number of *external* details (semantically specific details) as controls (F (1, 27) = 0.590, p = 0.449, η^2 = 0.02; Fig. 2b). The proportion of *internal* to *total* details was significantly lower in TLE patients than in controls (0.67 (SD = 0.12) and 0.78 (SD = 0.06), respectively; F (1, 27) = 9.223, p = 0.005, η^2 = 0.26).

Our sample of individuals with TLE was heterogeneous and included patients with left and right seizure foci who were tested either before or after surgery. Although these factors were not found in previous studies to be important in determining the magnitude of impairment in autobiographical memory retrieval (St-Laurent et al., 2009; Viskontas et al., 2000), it is possible that problem solving on the MEPS might be particularly disrupted in one of the subgroups, particularly in patients with removed temporal neocortex on the language-dominant side. Given our hypothesis about MTL-linked episodic involvement in this task, it was important to determine whether the problem solving impairment was seen in all patient subgroups regardless of laterality and surgical status. As a first step, box-plots were created that plotted scores for individual participants categorized by group (controls, pre-surgery left TLE patients, post-surgery left TLE patients, pre-surgery right TLE patients, and post-surgery right TLE patients; see Fig. 3). As seen in these box-plots, there is no patient group that is distinguishable from the others, indicating that the effect of laterality or surgical status on the results is minimal at most.

This conclusion was further supported by the results of a power analysis conducted to determine the number of participants needed to detect a significant difference between left and right TLE participants given the effect size in this sample. Setting the α at 0.05, to achieve a power of 0.80, 184 participants (left and right TLE participants) would be needed to find a laterality effect for the number of relevant means, and 840 to find a laterality difference for internal details. A similar power analysis indicated that a sample size of 86 and 322 participants would be needed to find a difference between pre and post surgery patients for relevant means and internal details, respectively.

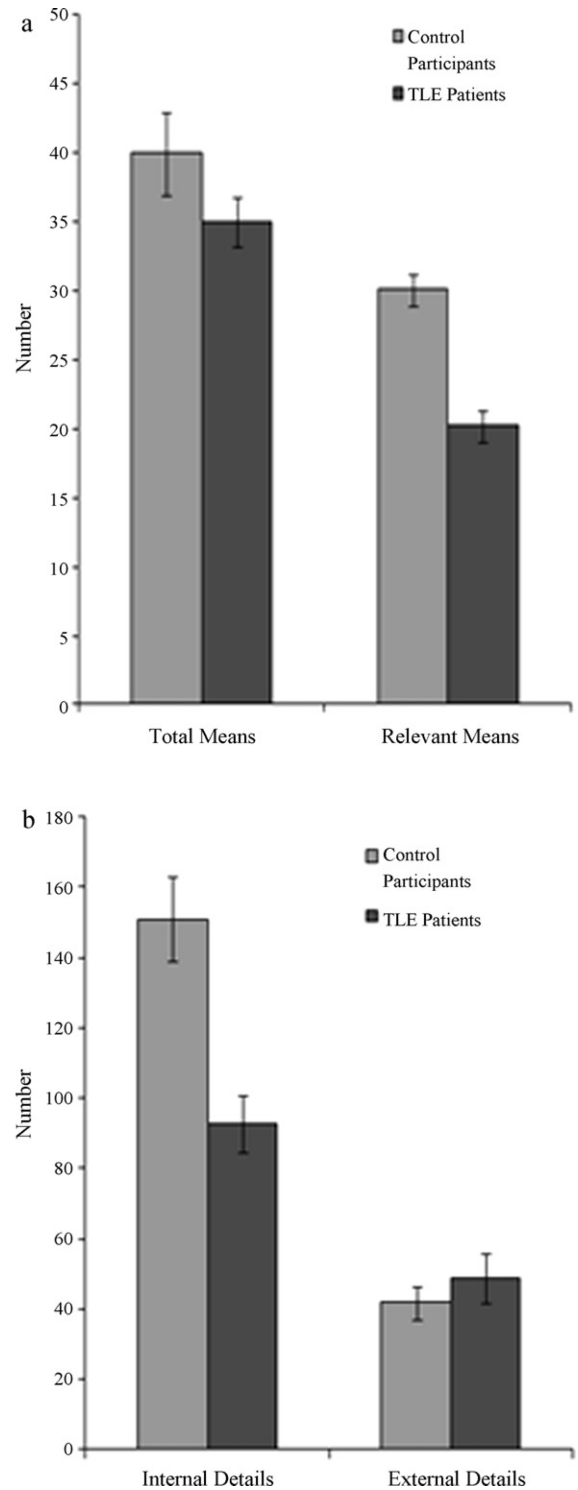

Fig. 2. (a) The average number of total means and relevant means given by patients with TLE and matched controls on the Means-End Problem Solving test. (b) The average number of internal and external details given by patients with TLE and matched controls on the Means-End Problem Solving test.

Across all participants, there was a significant positive correlation between number of relevant means and internal details (r = 0.74, p < 0.001), but not external details (r = 0.001, p > 0.50). In analyzing groups separately, power is significantly reduced

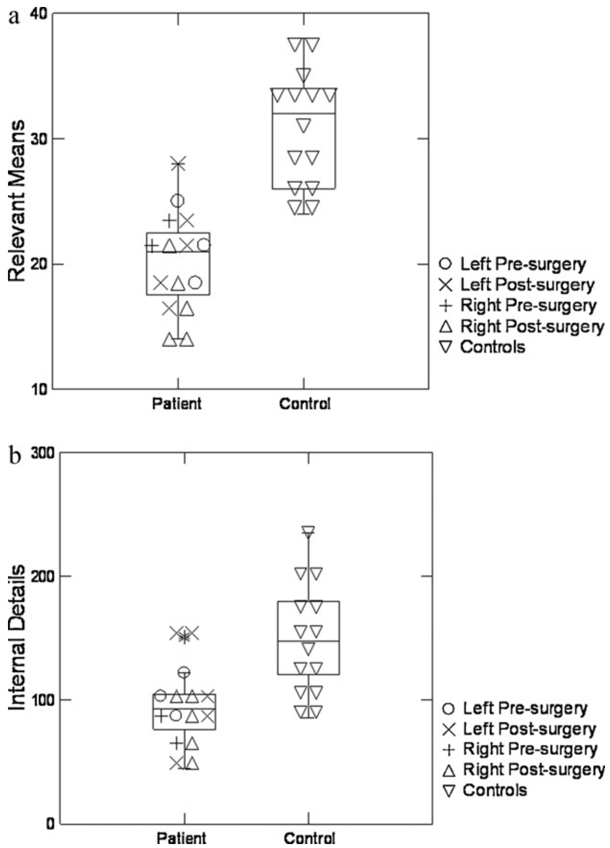

Fig. 3. (a) A boxplot of the number of relevant means generated by TLE patients, as categorized by their respective surgical and lateral groups, and controls on the MEPS. (b) A boxplot of the number of internal details generated by TLE patients, as categorized by their respective surgical and lateral groups, and controls on the MEPS.

so that a correlation of 0.52 would be required to achieve significance at $p < 0.05$ (or 0.45 for a one-tailed test) with an n of 15. Nonetheless, an examination of the group correlations resulted in a similar pattern for patients ($r = 0.47$ for relevant means and internal details and $r = 0.02$ for relevant means and external details) and controls ($r = 0.59$ for relevant means and internal details and $r = 0.47$ for relevant means and external details). Also, across both groups there was a significant positive correlation between the number of *irrelevant/no means* and external details ($r = 0.57$, $p = 0.004$), but not internal details ($r = 0.06$, $p = 0.77$).

As a secondary analysis, correlational analyses between MEPS scores and standard neuropsychological measures were conducted in the patient group, as neuropsychological testing was only administered to them. Again, we note that the small sample size ensures that only large effect sizes ($r > 0.52$) will reach statistical significance. Correlations in accord with a moderate relationship were found between a measure used to characterize episodic memory, delayed RAVLT scores, and the proportion of relevant means ($r = 0.50$, $p = 0.07$) but not with internal details ($r = 0.30$, $p = 0.30$). Even stronger (and statistically significant) correlations were found for category fluency and both internal details ($r = 0.57$, $p = 0.03$) and relevant means ($r = 0.62$, $p = 0.02$) ratios. Turning to other neuropsychological tests, we found weak correlations between a measure of general intelligence, FSIQ, and both relevant means and internal details ($r = 0.08$, $p = 0.77$, $r = 0.11$, $p = 0.71$, respectively) and between phonemic fluency and relevant means and internal details ($r = 0.19$, $p = 0.52$, $r = 0.01$, $p = 0.97$, respectively).

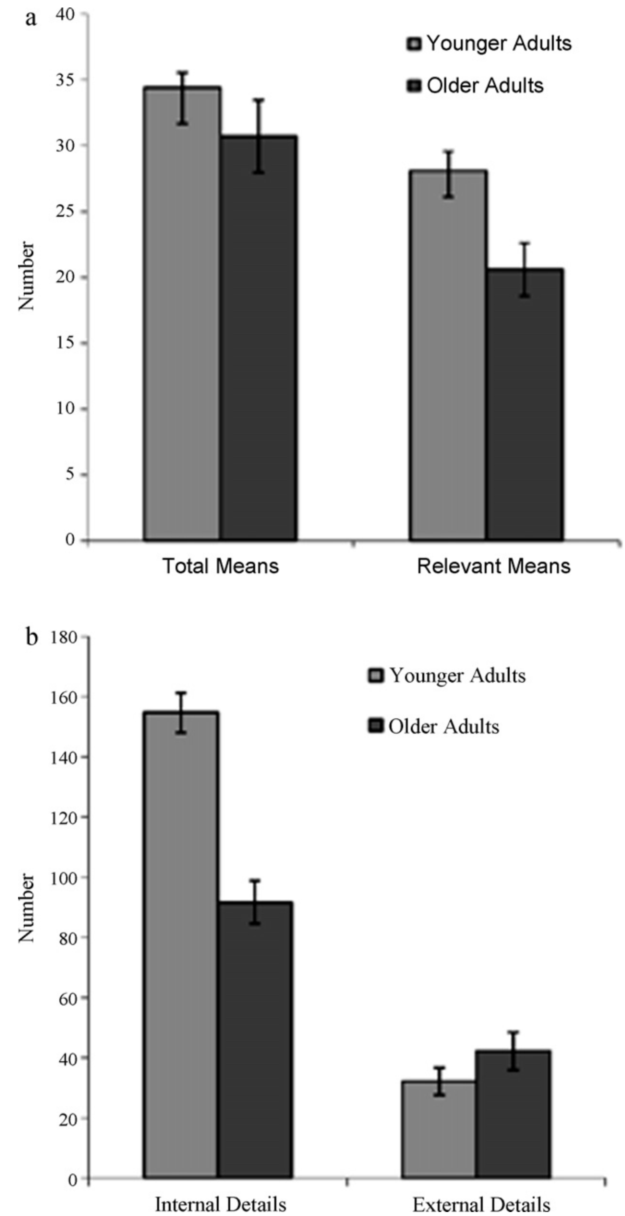

Fig. 4. (a) The average number of total means and relevant means given by younger and older adults on the Means-End Problem Solving test. (b) The average number of internal and external details given by younger and older adults on the Means-End Problem Solving test.

2.2. Experiment 1b: older adults and younger adults

2.2.1. MEPS means and details

Older and younger adults produced the same number of *total* (*irrelevant* plus *relevant*) means when solving problems (F (1, 28) = 1.895, $p = 0.180$, $\eta^2 = 0.10$). A repeated measures of ANOVA with mean type (relevant and irrelevant/no means) as a within-subject factor and group (older and younger adults) as a between-subject factor revealed a significant interaction effect, F(1, 28) = 15.489, $p < 0.001$. Further analyses revealed that older adults produced significantly fewer *relevant* means than younger adults (F (1, 28) = 9.834, $p = 0.004$, $\eta^2 = 0.26$; Fig. 4a).

When the solutions were scored using the Autobiographical Interview scoring technique, there was a significant interaction between detail type and group, F (1, 28) = 53.498, $p < 0.001$. The number of *internal* details was significantly greater in younger adults (F (1, 28) = 41.871, $p < 0.001$, $\eta^2 = 0.60$), but the number of

Table 2
Average scores for older adults on neuropsychological measures. Standard deviations are in parentheses.

Mini-Mental Status Exam (MMSE; maximum = 30)	29 (1.4)
Digit Span Backwards (maximum = 14)	6.8 (1.8)
Phonemic (FAS) fluency	39.8 (8.1)
Category (animal) fluency	21.7 (6.7)
Verbal Paired Associates I (total score; maximum = 32)	16.0 (7.2)
Verbal Paired Associates II (total score; maximum = 8)	5.6 (1.8)

external (semantically derived) details did not differ between the groups ($F(1, 28) = 1.733$, $p = 0.199$, $\eta^2 = 0.10$; Fig. 4b). Even when we controlled for the total number of details by examining the proportion of details that were *internal*, we still found that older adults had a significantly lower proportion of *internal* details than did younger adults ($M = 0.70$ (SE = 0.02) and $M = 0.83$ (SE = 0.02), respectively; $F(1, 28) = 18.105$, $p < 0.001$, $\eta^2 = 0.40$).

For all participants there was a significant positive correlation between the number of relevant means and internal details ($r = 0.694$, $p < 0.001$), but not external details ($r = -0.047$, $p = 0.805$), a pattern that held when each group was examined separately (Younger adults: $r = 0.34$ for internal details and $r = -0.43$ for external details; Older adults: $r = 0.75$ for internal details and $r = 0.39$ for external details).

2.2.2. Autobiographical memory recall

Only older adults participated in the autobiographical memory recall session. The number of internal details associated with past memories was significantly and positively correlated with the number of internal details given in the problem solutions ($r = 0.735$, $p = 0.004$) as well as with the number of relevant means ($r = 0.628$, $p = 0.012$). Conversely, the number of external details associated with past memories was not significantly correlated with the number of internal or external details given in the problem solutions ($r = -0.022$, $p = 0.938$; $r = -0.082$, $p = 0.772$, respectively) or with the number of relevant means given in the problem solutions ($r = 0.379$, $p = 0.163$).

2.2.3. Neuropsychological tests

While our main interest was in the group differences, we also conducted subsidiary analyses looking at correlations between the MEPS and neuropsychological measures. The mean results from the neuropsychological tests for older adults are reported in Table 2. As stated in the first half of this experiment, given the small n and the multiple neuropsychological tests given (only large effects will reach significance), we discuss the relations of these instead of significance. There were weak correlations between executive function tests and the number of internal details given in the problem solving test (backward digit span, $r = 0.30$, $p = 0.44$; phonemic fluency, $r = -0.14$, $p = 0.96$) as well as with the number of relevant means (backward digit span, $r = 0.28$, $p = 0.32$; phonemic fluency, $r = 0.27$, $p = 0.31$). There were also weak correlations between verbal paired associates (VPAI or VPA II) scores, a test of relational memory (after we removed three confused participants), and the number of internal details ($r = 0.30$, $p = 0.31$; $r = 0.30$, $p = 0.41$, respectively) and the number of relevant means ($r = 0.12$, $p = 0.74$; $r = 0.03$, $p = 0.93$, respectively). There was, however, a strong positive correlation between category fluency and internal details reported in the problems solving test ($r = 0.64$, $p < 0.05$), and a more modest correlation between category fluency and external details ($r = 0.33$, $p = 0.25$).

3. Discussion

The results of these experiments indicate that finding effective solutions to open-ended problems, such as the MEPS, is related to the vividness or richness of the simulation which, in turn, is related to episodic memory processes likely mediated by the MTL. Converging evidence from three sources support this interpretation. (1) Effective solutions to open-ended social problems, as measured by the number of *relevant* means to the problem solution, was deficient in both older adults and people with TLE, both of whom have episodic memory loss associated with medial temporal lobe deterioration, and damage, respectively. (2) Both TLE patients and older adults provided less detailed solutions, as measured by the number of internal (episodic) details, but not external (general) details than matched healthy and young controls, respectively. More importantly, there was a significant correlation in TLE patients and controls, and in healthy young and older adults, between the number of internal, but not external details, that were generated and the number of relevant means provided as solutions. (3) The number of internal details and relevant means on the problem solving task also were highly correlated with the number of internal, but not external, details on a test of autobiographical memory in older adults, the only group administered this test. Evidence from prior studies has shown that the vividness and richness of autobiographical memory as assessed by the number of internal details is associated with medial temporal lobe function, particularly that of the hippocampus (for review see Moscovitch, Nadel, Winocur, Gilboa, & Rosenbaum, 2006) and with performance on tests of episodic memory (Addis, Moscovitch, et al., 2007; Addis, Wong, et al., 2007).

The relation between problem solving and episodic memory in older adults and in patients with TLE suggests that even mild episodic memory deficits can be associated with impaired problem solving. The deficits seen in TLE patients are not likely to be related to the constellation of potential non-memory problems associated with epilepsy as older healthy adults performed similarly. The deficient problems solving abilities of both groups and the reduced number of internal details also cannot be attributed to a difference in output between them and their respective controls because such differences were not observed with respect to the number of external (general) details and the total word output on the MEPS. Likewise, the MEPS scores did not correlate with tests of frontal, executive functions in older adults, nor with these tests and IQ in TLE patients. Both sets of results indicate that the deficient performance on the MEPS was not due to some general cognitive deterioration due to aging or epilepsy.

There was no suggestion that side of lesion or surgery status affected performance for the TLE patients on the MEPS. The lack of effect related to either variable is consistent with other studies that used comparable narrative tests, such as the Autobiographical Interview with TLE patients (St-Laurent et al., 2009; Viskontas et al., 2000).

The correlations of performance on the MEPS with standard neuropsychological tests of memory were variable. For patients with TLE, there was a moderate correlation between proportion of relevant means and delayed RAVLT. For older adults, we used the VPA as a measure of relational memory. Although the VPA is not the best test to be used for correlational measures (Uttl, Graf, & Richter, 2007), we included it because it was part of a battery used by Addis et al. (2008) to examine the relation between tests of autobiographical, future thinking, and relational memory. While our correlational results was not significant, our correlations were comparable to those reported by Addis et al. (2008) when one of the outliers in their study, whose scores contributed inordinately to the correlations, was removed. Taking these results with others from this experiment, the fact that we found a strong correlation between MEPS scores and performance on the Autobiographical Interview for older adults in terms of the number of internal details generated, but not with this more standard measure of episodic memory, may mean that the MEPS is tapping into processes similar to those needed in recalling old memories rather than processes needed for retrieving recent novel relations. That is, it could be that the underlying processes needed for the Autobiographical Interview such as reconstructing remote memories and integrating episodic detail with semantic components in a narrative, is more similar to those needed to solve MEPS problems than the processes that are required to recall more recently acquired, novel associations among unrelated items.

Although performance on the MEPS is also likely to be sensitive to prefrontal integrity, as indexed by the neuropsychological tests we administered, this is outweighed by that of the medial temporal lobes. Despite these findings, it is important to note that neither our results nor those of the other investigators should be interpreted to mean that semantic memory and executive functions do not contribute to solving these and other such problems. Many studies have indicated an important role for executive functions in problem solving and planning (e.g., Davidson & Sternberg, 2004; Morris, Miotto, Feigenbaum, Bullock, & Polkey, 1997) and our study does not discredit those or argue against the importance of executive functions mediated by prefrontal cortex to problem solving. It is possible that had we used a more extensive battery of frontal-sensitive tests significant correlations with performance on the MEPS may have been found. Our findings, however, highlight the important role played by episodic memory in problem solving that has been relatively neglected to date. As we noted earlier, for the present study, the absence of correlation on the MEPS with age-sensitive executive function tests, such as backward digit span, and general IQ indicates that the correlations we observed with performance on tests of episodic memory cannot be attributed to general cognitive deterioration.

Altogether, our results demonstrate that the ability to solve open-ended social problems effectively is related to processes underlying episodic memory likely mediated by the medial temporal lobes and the hippocampus in particular. We are mindful, however, that the populations we studied also have damage or dysfunction outside of the hippocampus, and that although there is a substantial literature that points to the hippocampus as critical both for episodic recollection and simulation (for examples, see Addis, Moscovitch, et al., 2007; Addis, Sacchetti, Ally, Budson, & Schacter, 2009; Addis, Wong, et al., 2007; Hassabis et al., 2007), this view is not held universally (e.g., Squire et al., 2010). Our provisional suggestion that the hippocampus is implicated here awaits corroboration from future research.

Extrapolating from our findings and others in the literature, we speculate that episodic memory processes, specifically those that mediate reconstruction, contribute to solving open-ended problems in general. Our speculation is consistent with observations that impaired episodic memory is linked to poor social problem solving in older adults (Beaman et al., 2006) and in depressed people (Goddard et al., 1996; Williams et al., 2006). Other researchers have found that patients with amnesic mild cognitive impairment have difficulties with daily living problems that are related to their impaired episodic memory (Schmitter-Edgecombe, Woo, & Greeley, 2009). Using functional neuroimaging, investigators reported that in comparison to closed-ended tasks, completing open-ended tasks using event simulation (Abraham, Schubotz, & von Cramon, 2008) or free association (Whitney, Grossman, & Kircher, 2009) was related to activity in the episodic memory network, which included the medial temporal lobe structures, including the hippocampus.

The latter studies support our prediction that the relation between episodic memory abilities and problem solving is greatest when problems are ill-defined or open-ended than when problems are well-defined or closed-ended. Thus, in contrast to their impaired performance in solving open-ended problems, people with poor episodic memory typically perform as well as controls when asked to provide solutions or generate scripts for well-defined tasks, such as changing a tire or doing the laundry (Duff et al., 2008; St-Laurent et al., 2009).

Our study extends research on future thinking (Addis, Wong, et al., 2007), scene construction (Hassabis et al., 2007) and imagination (Rosenbaum et al., 2009) by showing not only that simulating possible scenes and scenarios is related to processes and neural mechanisms that mediate episodic memory, but that there also is a strong relationship between the richness and vividness of the simulation as measured by internal details and effectiveness in solving open ended problems. The contribution of episodic simulation is not restricted to solving complex open-ended problems, such as those that form the MEPS, but can be observed even in such simple tasks such as generating exemplars from a semantic category, such as animals or fruit (Greenberg, Keane, Ryan, & Verfaellie, 2009; Ryan, Cox, Hayes, & Nadel, 2008; Sheldon & Moscovitch, submitted for publication). Once the prototypical exemplars are exhausted, the individual simulates a scene or scenario (visiting a zoo, or walking the produce isles of a supermarket), and draws on information from episodic memory to generate the appropriate items (Sheldon & Moscovitch, submitted for publication). This may explain the strong correlations we found between measures of category fluency and internal details on the MEPS.

It remains to be determined exactly which processes in episodic memory are related to the ability to solve open-ended problems. Open-ended problems, like those used in the MEPS, have no defined steps or algorithm which can be applied to reach a solution, which requires creativity both in identifying the problem/solution space, and generating alternatives. Due to their indeterminacy, solutions to open-ended problems likely are not stored and retrieved from semantic memory (Pillemer, 2003) whose representations are more static and less flexible than those of episodic memory (Eichenbaum et al., 1992; Moscovitch, 2008). It is this flexibility in representation associated with episodic memory combined with the ability to bind unrelated material into a new relational representation (relational binding) that makes processes underlying episodic memory ideally suited for simulating detailed scenarios that can aid in solving open-ended problems.

Extending from this, we speculate that two aspects underlying episodic memory are involved in such problem solving, one operating at the beginning of the process and the other at the end. In order to identify the problem space and retrieve the information that is appropriate to a particular problem, the individual needs to appreciate the similarity between the particular problem and others that resemble it. The role of the hippocampus in pattern completion may serve this purpose: Elements from the current problem would activate memories of past episodes that share those elements and make them available at retrieval. The details of these episodic memories then serve as the building material at the end of the process (Moscovitch, 2008) when their flexible recombination into a coherent, but new, goal-oriented scenario completes the simulation process. One or more of these processes contribute to event simulation which, in turn, helps problem solving by gathering together elements of relevant experiences and providing a framework for planning and possibly for verifying the validity of the events or solutions (Conway, 2009; Pham & Taylor, 1999).

In summary, our results indicate that the vividness and richness of episodic simulations and episodic memories are closely linked with the ability to provide effective solutions to open-ended problems. As a result, even relatively mild memory loss, such as that experienced by patients with unilateral TLE and healthy older adults, is detrimental to solving open-ended problems. It is our hope that investigations which have already begun will increase our understanding of how the component processes mediating episodic memory, and their interaction with one another and with executive functions and semantic memory, relate to open-ended problem solving.

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