Brief Communication

Spared perception of object geometry and object components after hippocampal damage

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We tested the proposal that medial temporal lobe (MTL) structures support not just memory but also high-level object perception. In one task, participants decided whether a line drawing could represent an object in three-dimensional space and, in another task, they saw the components of an object and decided what object could be formed if the components were assembled. Patients with hippocampal lesions were intact, indicating that the hippocampus is not needed for perceiving the structural coherence of objects or appreciating the relations among object parts. Patients with large MTL lesions were moderately impaired, likely due to damage outside the MTL.

The medial temporal lobe (MTL) is essential for the formation of long-term declarative memory, and damage to the MTL produces severe forgetfulness (Milner 1972; Squire and Zola-Morgan 1991; Gabrieli 1998). Intellectual and perceptual functions have appeared to be intact (Milner et al. 1968; Milner 1972; Squire et al. 2004; Shrager et al. 2006), suggesting that memory is separable from other cognitive functions.

It has been suggested that the distinction between memory and other cognitive functions may not be so sharp as originally supposed. For example, MTL lesions have been reported to impair certain tasks of visual perception, in particular tasks that require discriminating among objects that have a high degree of feature overlap (Bussey and Saksida 2005; Lee et al. 2005a; Baxter 2009; Graham et al. 2010). Damage to perirhinal cortex was proposed to be responsible for these impairments (Bussey et al. 2002, 2003; Lee et al. 2005b,c; Barense et al. 2007). In addition, hippocampal lesions were reported to impair performance on certain tasks that involve discriminating among scenes when spatial features are important (Lee et al. 2005b,c; Graham et al. 2006) or representing information about the relations among objects and their parts (Warren et al. 2012).

The interpretation of these impairments has been the focus of considerable discussion (Suzuki 2009, 2010; Lee and Rudebeck 2010; Squire and Wixted 2011). One issue is that tasks often allow for a contribution of memory to task performance and would therefore disadvantage memory-impaired patients. For example, patients with hippocampal lesions were impaired at visual discrimination when stimuli were repeated across trials, but were intact when stimuli were unique on every trial (Kim et al. 2011). In addition, even when material is trial-unique, the number and complexity of the stimuli might exceed what can be managed by working memory as participants shift attention among parts of a display (Lee and Rudebeck 2010; for review, see Jeneson and Squire 2012). In this circumstance, performance would need to depend on long-term memory. Consistent with this idea, patients were intact when they needed to identify the unique object in a display of objects having a few features but were impaired when the display consisted of more objects and more features (Knutson et al. 2012). Notably, when an aid was provided to reduce the burden on working memory, patients performed as well as controls with all displays (Knutson et al. 2013). Finally, as discussed previously (Suzuki 2009), in some patients the damage appears to extend into the lateral temporal lobe, making it difficult to isolate an impairment to MTL structures.

As suggested previously (Lee and Rudebeck 2010), tests of visual perception and MTL function might avoid some of these difficulties by asking for judgments about unique single objects. In the present study, we administered two tasks. In the object decision task (Fig. 1A), participants judged whether an unfamiliar object could exist in three-dimensional space (Schacter et al. 1990). An earlier study using this task included a single patient with hippocampal lesions and a second patient with large MTL lesions (Lee and Rudebeck 2010). We tested five patients with circumscribed hippocampal lesions and two patients with large, well-characterized MTL lesions. In the Hooper Visual Organization Test (HVOT; Hooper 1985), participants viewed two to four components of a familiar object and decided what object the pieces might represent if they were assembled (Fig. 1B). An earlier study reported impairments in this and three related tasks in both hippocampal patients and patients with large MTL lesions (Warren et al. 2012). We tested six patients with hippocampal lesions and one patient with large MTL lesions.

The object decision task consisted of 40 possible and 40 impossible drawings. Following five practice trials with feedback, participants saw the 80 drawings one at a time at the center of a computer screen (visual angle = 8.0° × 9.7°) and pressed one of two keys to indicate "possible" or "impossible." Testing was self-paced with no feedback.

The HVOT consisted of 30 items ordered from easiest to most difficult. Testing was self-paced (mean response time = ~10 sec).

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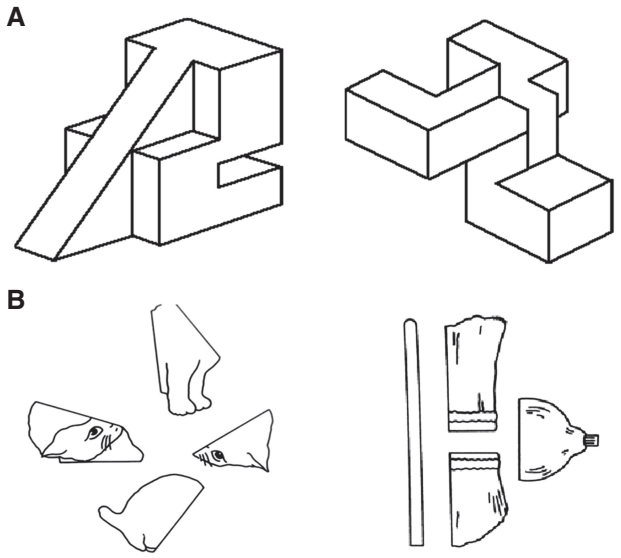

Figure 1. Sample items from the object decision task and the HVOT. (*A*) Participants decided whether an object could or could not exist in three-dimensional space. The drawing on the *left* depicts a possible object, and the drawing on the *right* depicts an impossible object. (*B*) Participants decided what object could be formed if the components were assembled. The elements in the *left* panel combine to depict a cat (Item 20). The elements in the *right* panel combine to depict a broom (Item 30).

Feedback was given for the first item. Eleven items allowed for half-point responses. For example, "cat" earned one point and "animal" earned 0.5 points (Fig. 1B, left) (maximum score for the test = 30 points).

Eight memory-impaired patients participated, six with bilateral lesions thought to be limited to the hippocampus (CA fields, dentate gyrus, and subicular complex) and two with large MTL lesions (Table 1). Patients D.A., R.S., and G.W. became amnesic in 2011, 1998, and 2001, respectively, following a drug overdose and associated respiratory failure. J.R.W. became amnesic in 1990 following an anoxic episode associated with cardiac arrest. K.E. became amnesic in 2004 after an episode of ischemia associated with kidney failure and toxic shock syndrome. L.J. (female) became amnesic during a 6-mo period in 1988 with no known precipitating event. Her impairment has been stable since then. The patients with large MTL lesions (E.P. and G.P.) developed severe memory impairment following viral encephalitis (in 1992 and 1987, respectively).

Estimates of MTL damage were based on quantitative analysis of magnetic resonance (MR) images from 19 age-matched, healthy males for K.E., R.S., G.W., J.R.W., E.P., and G.P., 11 age-matched, healthy females for L.J. (Gold and Squire 2005), and eight younger healthy males for D.A. Patients D.A., K.E., L.J., R.S., G.W., and J.R.W. have an average bilateral reduction in hippocampal volume of 35%, 49%, 46%, 33%, 48%, and 44%, respectively (all values ≥2.9 SDs below control mean). On the basis of two patients (L.M. and W.H.) with similar bilateral volume loss in the hippocampus for whom detailed postmortem neurohistological information was obtained (Rempel-Clower et al. 1996), the degree of volume loss in these six patients may reflect nearly complete loss of hippocampal neurons. The volume of the parahippocampal gyrus (temporopolar, perirhinal, entorhinal, and parahippocampal cortices) is reduced by −5%, 11%, −17%, −5%, 10%, and 12%, respectively (all values <2 SDs of control mean for the parahippocampal gyrus as well as for each of its subsections). The negative values indicate volumes larger for a patient than for controls. These values are based on published guidelines for identifying the boundaries of the parahippocampal gyrus (Insausti et al. 1998; Frankó et al. 2014).

E.P. and G.P. have an average bilateral reduction in hippocampal volume of 97% and 96%, respectively, and similarly large reductions in the parahippocampal gyrus (94%). Eight coronal MR images for seven patients (all but E.P.), together with detailed descriptions of the lesions, can be found elsewhere (Knutson et al. 2013). E.P.'s damage was described in detail on the basis of postmortem neurohistological analysis (Insausti et al. 2013), which also revealed shrunken lateral temporal lobes bilaterally.

G.P. has a reduction of 24% (>3 SDs below control mean) and 6% (<1 SD below control mean) in the left and right lateral temporal lobe, respectively. The volumes of the lateral temporal lobes were calculated for G.P. and 14 age-matched controls using FreeSurfer (version 5.1; Dale et al. 1999; Fischl et al. 1999, 2002, 2004), and included gray and white matter from the fusiform and the inferior, middle, and superior temporal gyri. The volumes were adjusted with respect to total intracranial volume (Buckner et al. 2004). Manual intervention corrected errors associated with boundaries between the brain and pia/skull and between gray and white matter.

The object decision task was given to seven patients (all but R.S.) and 16 controls (2 females; mean age = 67.5 ± 3.4 yr; mean education = 14.8 ± 0.8 yr). The HVOT was given to seven patients (all but E.P.) and nine controls (3 females; mean age = 64.3 ± 3.6 yr; mean education = 14.0 ± 0.5 yr). All procedures were approved by the Institutional Review Board at the University of California San Diego, and participants gave written informed consent.

The five patients with damage limited to the hippocampus performed as well as controls on the object decision task (accuracy,

Table 1. Characteristics of memory-impaired patients

				WMS-R				
Patient	Age (years)	Education (years)	WAIS-III IQ	Attention	Verbal	Visual	General	Delay
D.A.	31	12	95	104	90	91	90	56
K.E.	73	13.5	108	114	64	84	72	55
L.J.	77	12	101	105	83	60	69	<50
R.S.	58	12	99	99	85	81	82	<50
G.W.	55	12	108	105	65	86	70	<50
J.R.W.	51	12	90	87	65	95	70	<50
E.P.	81	12	98	94	59	82	68	56
G.P.	68	16	98	102	79	62	66	50

WAIS-III is the Wechsler Adult Intelligence Scale-III and the WMS-R is the Wechsler Memory Scale-Revised. The WMS-R does not provide numerical scores for individuals who score <50. IQ scores for R.S. and J.R.W. are from the WAIS-Revised, and the IQ score for D.A. is from the WAIS-IV.

86.3 ± 5.1% versus 87.7 ± 2.2% correct for controls; discriminability [d′], 2.5 ± 0.5 versus 2.8 ± 0.2; Fig. 2A,B). However, the two patients with large MTL lesions were moderately impaired (accuracy, 76.9 ± 0.6% versus 87.7 ± 2.2% correct, $P < 0.01$; discriminability [d′], 1.5 ± 0.1 versus 2.8 ± 0.2, $P < 0.001$). The impairment was particularly pronounced when impossible objects were presented (impossible objects, 72.5 ± 2.5% for patients versus 84.8 ± 3.9% for controls, $P < 0.05$; possible objects, 81.3 ± 3.8% versus 90.6 ± 2.9%, $P = 0.16$).

Response times were similar across groups (Fig. 2C), and there was no evidence of response bias (i.e., no preference for responding "possible" or "impossible," Fig. 2D). One MTL patient (G.P.) was available for a second testing more than a year later and obtained a similar score (first, 76.3% versus second, 79.7% correct).

Hippocampal patients, the MTL patient G.P., and controls performed similarly across all 30 test items of the HVOT (80.3 ± 3.9%, 80.0%, and 80.4 ± 4.2% correct, respectively). However, G.P. performed poorly on the last, most difficult block of five items (Fig. 3), receiving half-point credit for one item and no credit for the other items. He was also tested a second time more than a year later and performed similarly (i.e., scoring well on the first five blocks and 10% correct on the last block).

The current study and the earlier study that used the object decision task (Lee and Rudebeck 2010) converge in showing that the hippocampus is not needed to perform the object decision task. Note that recent studies raise the possibility that the hippocampus could be important for possible/impossible decisions in more complex tasks that require appreciating the spatial coherence of scenes (Douglas et al. 2017; McCormick et al. 2017).

The impairment observed in three patients with large MTL lesions (in our study and the earlier study by Lee and Rudebeck, 2010) raise the question of what structures other than the hippocampus might be important for the kind of high-level visual processing required by the object decision task. One suggestion is that perirhinal cortex is important (Lee and Rudebeck 2010). Yet, this is far from clear. Such a proposal depends on the idea that perirhinal cortex is a functional extension of the ventral visual pathway. However, this idea is not supported by cytoarchitectonic, connectional, or neurophysiological evidence. Rather, perirhinal cortex is a polymodal association area that is strongly connected with other MTL structures and that operates in the service of declarative memory (Suzuki and Amaral 1994; Suzuki 2010).

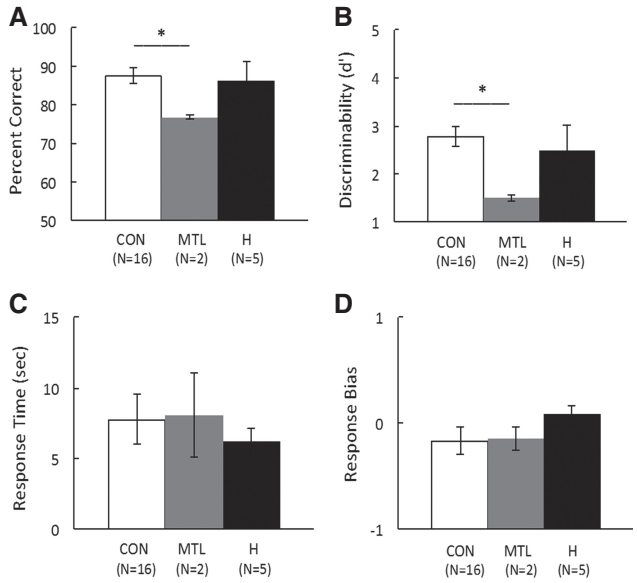

Figure 2. Performance on the object decision task. (*A*,*B*) Patients with damage limited to the hippocampus performed similarly to controls, but patients with large MTL lesions were impaired. The three groups had similar response times (*C*) and exhibited no response bias (*D*). (CON) controls, (H) hippocampal patients, (MTL) MTL patients. (*) $P < 0.01$.

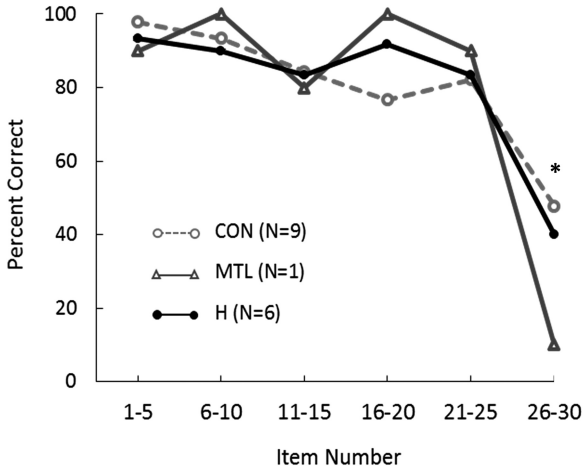

Figure 3. Performance on the HVOT. Patients with damage limited to the hippocampus performed similarly to controls across all blocks of items. Patient G.P. with large MTL lesions performed as well as controls on the first 25 items but performed poorly on the most difficult items (26–30). (CON) controls, (H) hippocampal patients, (MTL) MTL patient. (*) $P < 0.05$ for comparisons between the MTL patient and each of the other groups.

It is noteworthy that the three MTL patients in the two studies all had significant damage to anterior lateral temporal cortex. The MTL patient in Lee and Rudebeck (2010) had significant damage to temporopolar cortex, anterior fusiform gyrus, and anterior lateral temporal cortex on the right side. For our patient E.P., neurohistological findings showed his lateral temporal lobe to be substantially shrunken bilaterally (Insausti et al. 2013). Last, G.P. has a 24% volume reduction in the left lateral temporal lobe (>3SDs below control mean), mostly ventral and anterior. Thus, one possibility is that damage to anterior lateral temporal lobe is responsible for the impairment. Support for this idea comes from other studies that involve making decisions about objects. In one case, making semantic decisions about pictures (living or nonliving) was associated with neural activity in ventral anterior temporal lobe bilaterally (Visser and Lambon Ralph 2011). In another case, transcranial magnetic stimulation (TMS) directed to the anterior temporal lobe disrupted the ability to discriminate between animals or plants and similar-appearing artifacts (Chiou and Lambon Ralph 2016). The object decision task in our study shares with these other tasks the requirement to make judgments about the properties of objects.

Another possibility is that the parahippocampal place area (PPA; Epstein and Kanwisher 1998) is relevant to the impairment in the object decision task. The PPA encompasses posterior parahippocampal cortex and portions of the fusiform and lingual gyri (Marchette et al. 2015) and is involved in processing information about the geometry of surrounding space and in integrating information about complex objects into a coherent representation (Troiani et al. 2014).

Our findings for the HVOT differ from an earlier study that found a pronounced impairment on this same task in both hippocampal patients and patients with large MTL lesions (Warren et al. 2012). Our hippocampal patients were intact, and our patient with large MTL lesions was only moderately impaired. It is unclear why our findings did not replicate the earlier work with this rather

straightforward task. We did note that the task we gave was a little more difficult than when it was given in the earlier study. Specifically, our controls obtained a marginally worse score than the controls in the earlier study (80.3% for our controls versus 91.3% correct for their controls as estimated from individual *T*-scores in their Figure 1B and converted to percent correct scores according to the HVOT Manual; $t_{(12)} = 1.78$, $P = 0.10$; two-sample *t*-test). Yet, this difference does not appear to be relevant because the patients in the earlier study were impaired (estimated as 68.7% correct) even in comparison to our lower-scoring control group ($t_{(11.06)} = 2.50$, $P = 0.03$; two-sample *t*-test, unequal variance). Indeed, each of their five patients, including the three hippocampal patients, performed worse than our patient G.P. (80.0% correct), who has severe memory impairment and large MTL lesions that include virtually all of the hippocampus.

The fact that the patients in the earlier study performed worse than even G.P. raises the possibility that the impairment reported in the earlier study is related to damage outside the MTL. Anatomical information about these patients provides some support for this idea. First, two of the three hippocampal patients were earlier described as also having moderate to severe reduction in gray matter volume of the parietal lobes (Allen et al. 2006). In addition, the two patients with more extensive lesions had damage that included both "temporal and medial temporal lobes" (Warren et al. 2012; p.1579). One of them, as described in more detail in an earlier publication, had damage encompassing the entire right temporal lobe as well as severe damage to the orbital frontal cortex, insula, and anterior cingulate bilaterally (Feinstein et al. 2010). In view of the volume reduction in his left temporal lobe, our patient G.P.'s modest impairment (limited to the final block of trials) may also depend on damage outside the MTL.

In summary, findings for the object decision task indicate that the hippocampus is not needed for high-level object perception. Findings for the HVOT (i.e., intact performance after hippocampal lesions) differ from what had been reported earlier for this task (and three related tasks). Given some uncertainty about the extent of the lesions in the earlier study, we suggest that the hippocampus itself is not needed for the representation of information about objects and their components. Finally, we propose that the impairment reported in these tasks for patients with large MTL lesions depends on damage outside the MTL.

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References

Allen JS, Tranel D, Bruss J, Damasio H. 2006. Correlations between regional brain volumes and memory performance in anoxia. *J Clin Exp Neuropsychol* **28:** 457–476.

Barense MD, Gaffan D, Graham KS. 2007. The human medial temporal lobe processes online representations of complex objects. *Neuropsychologia* **45:** 2963–2974.

Baxter MG. 2009. Involvement of medial temporal lobe structures in memory and perception. *Neuron* **61:** 667–677.

Buckner RL, Head D, Parker J, Fotenos AF, Marcus D, Morris JC, Snyder A. 2004. A unified approach for morphometric and functional data analysis in young, old, and demented adults using automated atlas-based head size normalization: reliability and validation against manual measurement of total intracranial volume. *Neuroimage* **23:** 724–738.

Bussey TJ, Saksida LM. 2005. Object memory and perception in the medial temporal lobe: an alternative approach. *Curr Opin Neurobiol* **15:** 730–737.

Bussey TJ, Saksida LM, Murray EA. 2002. Perirhinal cortex resolves feature ambiguity in complex visual discriminations. *Eur J Neurosci* **15:** 365–374.

Bussey TJ, Saksida LM, Murray EA. 2003. Impairments in visual discrimination after perirhinal cortex lesions: testing 'declarative' vs. 'perceptual-mnemonic' views of perirhinal cortex function. *Eur J Neurosci* **17:** 649–660.

Chiou R, Lambon Ralph MA. 2016. The anterior temporal cortex is a primary semantic source of top-down influences on object recognition. *Cortex* **79:** 75–86.

Dale AM, Fischl B, Sereno MI. 1999. Cortical surface-based analysis. I. Segmentation and surface reconstruction. *Neuroimage* **9:** 179–194.

Douglas D, Thavabalasingam S, Chorghay Z, O'Neil EB, Barense MD, Lee AC. 2017. Perception of impossible scenes reveals differential hippocampal and parahippocampal place area contributions to spatial coherency. *Hippocampus* **27:** 61–76.

Epstein R, Kanwisher N. 1998. A cortical representation of the local visual environment. *Nature* **392:** 598–601.

Feinstein JS, Rudrauf D, Khalsa SS, Cassell MD, Bruss J, Grabowski TJ, Tranel D. 2010. Bilateral limbic system destruction in man. *J Clin Exp Neuropsychol* **32:** 88–106.

Fischl B, Sereno MI, Dale AM. 1999. Cortical surface-based analysis. II: Inflation, flattening, and a surface-based coordinate system. *Neuroimage* **9:** 195–207.

Fischl B, Salat DH, Busa E, Albert M, Dieterich M, Haselgrove C, van der Kouwe A, Killiany RJ, Kennedy D, Klaveness S, et al. 2002. Whole brain segmentation: automated labeling of neuroanatomical structures in the human brain. *Neuron* **33:** 341–355.

Fischl B, Van der Kouwe A, Destrieux C, Halgren E, Segonne F, Salat DH, Busa E, Seidman LJ, Goldstein J, Kennedy D, et al. 2004. Automatically parcelling the human cerebral cortex. *Cereb Cortex* **14:** 11–22.

Frankó E, Insausti AM, Artacho-Pérula E, Insausti R, Chavoix C. 2014. Identification of the human medial temporal lobe regions on magnetic resonance images. *Hum Brain Mapp* **35:** 248–256.

Gabrieli JDE. 1998. Cognitive neuroscience of human memory. *Annu Rev Psychol* **49:** 87–115.

Gold JJ, Squire LR. 2005. Quantifying medial temporal lobe damage in memory-impaired patients. *Hippocampus* **15:** 79–85.

Graham KS, Scahill VL, Hornberger M, Barense MD, Lee AC, Bussey TJ, Saksida LM. 2006. Abnormal categorization and perceptual learning in patients with hippocampal damage. *J Neurosci* **26:** 7547–7554.

Graham KS, Barense MD, Lee AC. 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:** 831–853.

Hooper HE. 1985. *Hooper visual organization test*. Western Psychological Services, Los Angeles.

Insausti R, Juottonen K, Soininen H, Insausti AM, Partanen K, Vainio P, Laakso MP, Pitkänen A. 1998. MR volumetric analysis of the human entorhinal, perirhinal, and temporopolar cortices. *Am J Neuroradiol* **19:** 659–671.

Insausti R, Annese J, Amaral DG, Squire LR. 2013. Human amnesia and the medial temporal lobe illuminated by neuropsychological and neurohistological findings for patient E.P. *Proc Natl Acad Sci* **110:** 1953–1962.

Jeneson A, Squire LR. 2012. Working memory, long-term memory, and medial temporal lobe function. *Learn Mem* **19:** 15–25.

Kim S, Jeneson A, van der Horst AS, Frascino JC, Hopkins RO, Squire LR. 2011. Memory, visual discrimination performance, and the human hippocampus. *J Neurosci* **31:** 2624–2629.

Knutson AR, Hopkins RO, Squire LR. 2012. Visual discrimination performance, memory, and medial temporal lobe function. *Proc Natl Acad Sci* **109:** 13106–13111.

Knutson AR, Hopkins RO, Squire LR. 2013. A pencil rescues impaired performance on a visual discrimination task in patients with medial temporal lobe lesions. *Learn Mem* **20:** 607–610.

Lee AC, Rudebeck SR. 2010. Human medial temporal lobe damage can disrupt the perception of single objects. *J Neurosci* **30:** 6588–6594.

Lee AC, Barense MD, Graham KS. 2005a. The contribution of the human medial temporal lobe to perception: bridging the gap between animal and human studies. *Q J Exp Psychol B* **58:** 300–325.

Lee AC, Buckley MJ, Pegman SJ, Spiers H, Scahill VL, Gaffan D, Bussey TJ, Davies RR, Kapur N, Hodges JR, et al. 2005b. Specialization in the medial temporal lobe for processing of objects and scenes. *Hippocampus* **15:** 782–797.

Lee AC, Bussey TJ, Murray EA, Saksida LM, Epstein RA, Kapur N, Hodges JR, Graham KS. 2005c. Perceptual deficits in amnesia: challenging the medial temporal lobe 'mnemonic' view. *Neuropsychologia* **43:** 1–11.

Marchette SA, Vass LK, Ryan J, Epstein RA. 2015. Outside looking in: landmark generalization in the human navigational system. *J Neurosci* **35:** 14896–14908.
McCormick C, Rosenthal CR, Miller TD, Maguire EA. 2017. Deciding what is possible and impossible following hippocampal damage in humans. *Hippocampus* **27:** 303–314.
Milner B. 1972. Disorders of learning and memory after temporal lobe lesions in man. *Clin Neurosurg* **19:** 421–466.
Milner B, Corkin S, Teuber HL. 1968. Further analysis of the hippocampal amnesic syndrome: l4 year follow-up study of H.M. *Neuropsychologia* **6:** 215–234.
Rempel-Clower NL, Zola SM, Squire LR, Amaral DG. 1996. Three cases of enduring memory impairment after bilateral damage limited to the hippocampal formation. *J Neurosci* **16:** 5233–5255.
Schacter DL, Cooper LA, Delaney SM. 1990. Implicit memory for unfamiliar objects depends on access to structural descriptions. *J Exp Psychol Gen* **119:** 5–24.
Shrager Y, Gold JJ, Hopkins RO, Squire LR. 2006. Intact visual perception in memory-impaired patients with medial temporal lobe lesions. *J Neurosci* **26:** 2235–2240.
Squire LR, Wixted JT. 2011. The cognitive neuroscience of human memory since H.M. *Annu Rev Neurosci* **34:** 259–288.
Squire LR, Zola-Morgan S. 1991. The medial temporal lobe memory system. *Science* **253:** 1380–1386.
Squire LR, Stark CEL, Clark RE. 2004. The medial temporal lobe. *Annu Rev Neurosci* **27:** 279–306.
Suzuki WA. 2009. Perception and the medial temporal lobe: evaluating the current evidence. *Neuron* **61:** 657–666.
Suzuki WA. 2010. Untangling memory from perception in the medial temporal lobe. *Trends Cogn Sci* **14:** 195–200.
Suzuki WA, Amaral DG. 1994. Perirhinal and parahippocampal cortices of the macaque monkey: cortical afferents. *J Comp Neurol* **350:** 497–533.
Troiani V, Stigliani A, Smith ME, Epstein RA. 2014. Multiple object properties drive scene-selective regions. *Cereb Cortex* **24:** 883–897.
Visser M, Lambon Ralph MA. 2011. Differential contributions of bilateral ventral anterior temporal lobe and left anterior superior temporal gyrus to semantic processes. *J Cogn Neurosci* **23:** 3121–3131.
Warren DE, Duff MC, Jensen U, Tranel D, Cohen NJ. 2012. Hiding in plain view: lesions of the medial temporal lobe impair online representation. *Hippocampus* **22:** 1577–1588.

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