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The Role of Recollection, Familiarity, and the Hippocampus in Episodic and Working Memory

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Abstract

The hippocampus plays an essential role in long-term episodic memory by supporting the recollection of contextual details, whereas surrounding regions such as the perirhinal cortex support familiarity-based recognition discriminations. Working memory - the ability to maintain information over very brief periods of time - is traditionally thought to rely heavily on frontoparietal attention networks, but recent work has shown that it can also rely on the hippocampus. However, the conditions in which the hippocampus becomes involved in working memory tasks are unclear and whether it contributes to recollection or familiarity-based responses in working memory is only beginning to be explored. In the current paper, we first review and contrast the existing amnesia literature examining recollection and familiarity in episodic and working memory. The results indicate that recollection and familiarity contribute to both episodic and working memory. However, in contrast to episodic memory, in working memory the hippocampus is particularly critical for familiarity-based rather than recollection-based discrimination. Moreover, the results indicate that the role of the hippocampus in working memory can be obscured due to 'criterion-induced process-masking' because it primarily supports intermediate-confidence recognition decisions. We then report results from a new working memory study examining the ability of amnesics to detect global and local changes in novel complex objects (i.e., fribbles), which indicates that the hippocampus plays an especially critical role in working memory when the task requires the detection of global rather than discrete changes. We conclude by considering the results in light of neurocomputational models and proposing a general framework for understanding the relationship between episodic and working memory.

Introduction

The ability to remember past episodes from our lives is essential for survival, and it is severely impaired in individuals with damage to the hippocampus, whether due to brain injury or age-related brain changes (Mayes & Downes, 1997; Nyberg, 2017; Scoville & Milner, 1957; Squire et al., 2004). These episodic memory deficits can often be observed even when working memory is well preserved. For example, amnesic patients with damage to the medial portions of the temporal lobe such as the hippocampus are often able to maintain a small number of items in memory for a short time (i.e., working memory), but are unable to remember that information over longer durations (e.g., Mayes & Downes, 1997; Squire et al., 2004). This dissociation supports the traditional conceptualization of

working memory as relying on attention and maintenance mechanisms supported by frontal and parietal regions that can operate independently of the hippocampus (Corbetta, 1998; Naghavi & Nyberg, 2005; Ptak, 2012; Ungerleider, 2000). However, a growing number of studies have identified conditions in which the hippocampus is critical for working memory (Moore et al., 2006; Ranganath & Blumenfeld, 2005; Ryan & Cohen, 2004), challenging the proposed neural dissociations between working and long-term memory. Determining the role of the hippocampus in supporting these two forms of memory is critical for testing current theories of both episodic and working memory function, as well as for characterizing the cognitive impairments of various populations suffering from damage and age-related changes to these brain regions and memory processes.

In the current paper, we examine the conditions in which the hippocampus contributes to visual working memory and episodic memory, and we aim to determine whether the role it plays in working memory is similar to its role in episodic memory. Namely, does the hippocampus support recollection or familiarity-based responses in working memory? We focus on working memory and episodic memory studies that have examined old/new recognition decisions for visual stimuli in which participants rate the confidence of their decisions (see Figure 1). This is because, as described in more detail below, these studies allow us to plot Receiver Operating Characteristics (ROCs) and so allow us to separate measures of memory sensitivity (i.e., memory accuracy) from response bias (i.e., the tendency to report memories). In doing so, they also allow us to assess the underlying memory processes that are impacted (i.e., does the hippocampus support conscious recollection of study events or assessments of familiarity?). We will argue that ROC results converge with results from a variety of other test procedures in showing that the hippocampus supports recollection in episodic memory tests, but that it supports familiarity in working memory tests. In the discussion, we consider how these results relate to other working memory tests such as those that do not require confidence ratings (e.g., old/new recognition, and free recall), those with longer delays (e.g., more than a few seconds), and those examining nonvisual materials (e.g., phonological or auditory stimuli).

We begin by briefly reviewing the literature on episodic memory and the hippocampus. We then consider the growing body of amnesic patient studies examining working memory and report a new patient study examining the effects of hippocampal damage on working memory for global vs discrete visual information. Finally, we relate those results to neurocomputational models of memory and consider a general framework for incorporating theories of working and episodic memory.

The role of the hippocampus in supporting recollection and familiarity in episodic memory.

Hippocampal damage impairs performance on episodic recognition tests, and it preferentially impairs high-confidence responses that are associated with conscious recollection of qualitative information about the study event, leaving familiarity-based recognition responses relatively unaffected (for reviews see Diana et al., 2007; Eichenbaum et al., 2007; Montaldi & Mayes, 2010; Yonelinas et al., 2010). The results are illustrated in Figure 2, in which amnesic patients with hippocampal damage and healthy controls received an item recognition confidence test for an earlier studied list of items such as words, objects,

or scenes. Receiver operating characteristics (ROCs) are plotted such that the leftmost point reflects the highest confidence recognition responses (i.e., 6 = 'I'm sure the item was studied'), with the hit rate (i.e., probability of accepting an old item as old) and the false alarm rate (i.e., probability of incorrectly accepting a new item as old) plotted on the y- and x-axes, respectively. Each subsequent ROC point includes the next most confident responses (e.g., the 6 plus 5 responses) in a cumulative manner.

The ROCs in the left panel of Figure 2 show that amnesic patients produce lower ROCs than age-matched controls, indicating that the patients exhibit reduced memory sensitivity across each level of response bias/confidence. Importantly, the deficits are particularly noticeable on the leftmost portion of the ROCs indicating that the patients' deficits are most pronounced for the highest confidence recognition responses. ROC performance can be quantified to estimate the likelihood of recollection and familiarity using a dual-process signal detection model (Yonelinas, 1994; Yonelinas et al., 2010) illustrated in the middle panel of Figure 2. The model assumes that new items have some baseline level of familiarity (i.e., the dashed distribution) and studied items are more familiar than new items, thus shifting the old item distribution to the right (i.e., the middle distribution). In this way, familiarity strength is directly related to response confidence (illustrated with vertical lines for confidence responses 1-6). In addition, however, because some proportion of old items will be recollected (i.e., participants can retrieve specific qualitative information about the study event such as 'I remember that this yellow building or this particular test word was one of the first items in the list'), this will increase the number of old items that elicit a high-confidence recognition response. When this model is fit to the observed ROCs it indicates that hippocampal damage reduces the proportion of recollected items and has little effect on familiarity strength (see right panel of Figure 2). Note that other common models such the unequal variance signal detection model (Green & Swets, 1966; Hautus et al., 2021) lead to similar conclusions; namely, that familiarity strength is relatively unaffected by hippocampal amnesia, whereas a second memory process that increases the variance of the old item distribution relative to the new item distribution is reduced in amnesia (Yonelinas & Parks, 2007).

Similar conclusions have been obtained from various other studies examining memory from numerous different patient groups, and a wide variety of different materials, as well as from studies using various other measurement methods such as remember/know, process dissociation, and structural equation modeling (Aggleton et al., 2005; Bastin et al., 2004; Bowles, 2010; Brandt et al., 2008; Fortin, 2004; Gilboa et al., 2006; Holstock, 2002; Jager et al., 2009; Mayes et al., 2002; Rudebeck, 2011; Turriziani et al., 2008; Vann, 2009; Yonelinas et al., 2002, 2004). We note that there are a small number of hippocampal patients that do appear to exhibit reductions in familiarity (Cipolotti et al., 2006; Manns et al 2003; Wixted & Squire, 2010), but whether those anomalous findings reflect measurement error or damage to regions outside the hippocampus is unknown (Eichenbaum et al., 2007; Quamme et al., 2004; Parks & Yonelinas, 2007). In addition, the method used to model ROC data has been criticized because it has been argued that it assumes that recollection is a threshold process whereby all recollected items must have the same memory strength (Wixted, 2007). This, however, has been shown to be a misunderstanding of threshold models, which actually assume that recollective strength can vary continuously, but that some proportion of items

fall below a memory threshold such that recollection sometimes fails (for further discussion of this issue see Parks & Yonelinas, 2007; Sherman, Atri, Hasselmo, Stern & Howard, 2003). Nonetheless, one should always be critical of any single measurement method or the results from any single group of participants, highlighting why it is important that the results have converged across many different studies examining different patient groups, using various different materials and various measurement methods.

In addition to studies of human patients with selective hippocampal damage, selective hippocampal lesions in rats lead to similar ROC results, indicating that hippocampal lesions produce selective deficits in recollection (Fortin, 2004; also see Robitsek et al., 2008). In addition, patients with damage to the fornix (a major output pathway from the hippocampus) and resulting mammillary body atrophy also exhibited selective recollection deficits (Vann et al., 2009). This was observed using both the ROC procedure and a remember/know procedure in which participants indicated when their recognition responses were accompanied by recollection of specific details about the study event (i.e., remembering) vs. familiarity in the absence of recollection (i.e., knowing). In addition, using structural equation modeling methods, Vann et al. (2009) found that mammillary body atrophy was related to deficits in recollection and was unrelated to familiarity.

In contrast, damage to the surrounding medial temporal lobe (MTL) regions such as the perirhinal cortex leads to deficits in familiarity. For example, patients with damage to both the hippocampus and the surrounding MTL cortex exhibit deficits in both recollection and familiarity (for review see Yonelinas et al., 1998). Moreover, patients with damage to the perirhinal or entorhinal cortex that does not influence the hippocampus exhibit selective familiarity deficits (for review see Köhler & Martin, 2020; also see Argyropoulos et al., 2022; Brandt et al., 2008). These results are consistent with structural equation modeling results of aging that have indicated that hippocampal volume is related to recollection whereas perirhinal/entorhinal volume is related to familiarity (Yonelinas et al., 2007; also see Schoemaker et al., 2016, 2017).

In addition to the lesion results, fMRI studies also indicate that the hippocampus is critical for recollection whereas surrounding MTL regions such as the perirhinal cortex are critical for familiarity (for review Diana et al., 2007). For example, in a recognition memory test for words (Yonelinas et al., 2005), old items that were confidently recollected ('R' responses) led to greater hippocampal activity than confidence responses that were based on familiarity (e.g., '4', '3', '2' or '1' responses) (see upper left portion of Figure 3). Similar results were reported by Montaldi, Spencer, Roberts and Mayes (Montaldi et al., 2006) in a recognition memory study for scenes, but in addition, they found that the perirhinal cortex activity decreased across levels of familiarity (i.e., 'F1', 'F2', 'F3'), but was not preferentially increased for remembered items ('R') (see upper right portion of Figure 3). Additional work from this lab showed that hippocampal activity was related to recollection and not familiarity for objects and scenes, whereas perirhinal cortex activity was related to familiarity strength for objects and both perirhinal and parahippocampal cortex activity were related to familiarity strength for scenes (Kafkas et al., 2017; also see Martin et al., 2013). This pattern of results suggests that the MTL cortical regions supporting familiarity are at least partially material specific. Further support for this observation is the finding that

left perirhinal cortex damage leads to a deficit in familiarity for verbal materials but not for visual materials (Martin et al., 2013), whereas the opposite is true of right hemisphere damage (Argyropoulos et al., 2022).

In sum, in episodic memory, results from neuropsychological, animal lesion, and human neuroimaging studies indicate that the hippocampus is critical in supporting high-confidence recognition responses that are accompanied by the subjective experience of conscious recollection whereby qualitative information about the study event is retrieved, rather than supporting familiarity-based recognition decisions. In contrast, other MTL regions such as the perirhinal cortex are critical in supporting intermediate-confidence familiarity-based recognition responses whereby items are accepted as old on the basis of memory strength.

These results are important in showing that episodic memory does not reflect a single monolithic form of memory, rather there are at least two functionally dissociable processes (i.e., recollection and familiarity) that contribute to performance in these types of tests, and so memory tests such as recognition do not provide pure measures of underlying memory processes (i.e., memory tests are not process-pure measures; Jacoby, 1991). It is important to acknowledge though that these results do not imply that there are ‘only’ two processes involved in recognition, as there are many additional perceptual and decision processes that are also necessary in supporting recollection and familiarity-based recognition decisions (e.g., Mayes & Roberts, 2001). Moreover, they also do not imply that these MTL regions operate in isolation, rather they appear to reflect critical hubs of much broader cortical and subcortical brain networks (e.g., Eichebaum et al., 2007; Diana et al., 2007; Ranganath & Ritchey, 2012; Ekstrom & Hill, 2023; Bastin et al., 2019). Finally, these results should not be interpreted as indicating that these MTL regions are limited to playing a role in episodic memory tasks or in supporting a single underlying cognitive process (i.e., there is no simple one-to-one mapping between memory processes and brain regions). As we will argue below, MTL regions can also play critical roles in working memory, and those roles can be quite different from the roles they play in episodic memory tasks.

The role of the hippocampus in supporting recollection and familiarity in working memory.

Most studies of recollection and familiarity have focused on episodic memory, but there is growing evidence that similar processes can also contribute to working memory (Feredoes & Postle, 2010; Oberauer & Lange, 2009; Aly & Yonelinas, 2012). That is, in some cases participants can maintain a number of items for a brief time such that they can recollect if one of them has changed, whereas in other cases they can make a response on the basis of familiarity. In addition, a number of studies have indicated that patients with hippocampal damage can be significantly impaired in working memory tests (e.g., Olson et al., 2006; Ranganath & Blumenfeld, 2005; Ryan & Cohen, 2004). These studies are important in showing that the hippocampus can be involved in working memory, but they have not directly addressed how it contributes to working memory performance. For example, one possibility is that when the capacity of working memory is exceeded – such as when the study-test delay increases beyond a few seconds or when the number of items studied exceeds 3 or 4 items – then long-term recollection may contribute to working memory performance. In that case, healthy controls may outperform the patients because the patients

have an episodic recollection impairment (Jeneson et al., 2006). However, several recent studies have begun to examine the role of the hippocampus in supporting recollection and familiarity-based working memory and perception using tasks with short delays and with very few items (Aly et al., 2013, 2014; Goodrich et al., 2019; Goodrich & Yonelinas, 2016). The results indicate that, in stark contrast to what has been observed in studies of episodic memory, in working memory hippocampal damage disrupts familiarity-based responses and does not reduce recollection responses.

In tests of perception and working memory, just as in tests of episodic memory, ROC studies have indicated that both recollection and familiarity processes can contribute to performance (Aly et al., 2013; Aly & Yonelinas, 2012; Goodrich et al., 2019; Goodrich & Yonelinas, 2016; for a review of behavioral ROC studies of working memory see Yonelinas, 2023). That is, for some proportion of trials, participants are highly confident that a change has occurred, and they can provide specific details of what has changed (i.e., participants can “recollect” what has changed). For other trials, participants can sense that a change has occurred, but they are unable to identify exactly what has changed (i.e., some test items just seem like they have changed). The distinction has been referred to as reflecting recollection vs. familiarity-based responding, seeing vs. sensing, or state- vs. strength-based responding (Aly et al., 2013; Rensink, 2004). Here, we will refer to these processes as “recollection vs. familiarity” for comparison to the episodic memory literature.

Several studies have examined confidence ROCs to determine the effects of hippocampal damage on recollection and familiarity in visual change detection tasks. For example, Aly et al., (2013) asked participants to indicate if two scenes were identical or if one was slightly changed (i.e., the images were either slightly pinched or expanded). In the example shown in Figure 4a, the windows near the center of the building are slightly closer together in the scene on the left than the scene on the right. The images were simultaneously presented for 1.5s and participants were free to move their eyes from one scene to the other. They were then required to make a 6-point confidence judgment indicating if the images were the same or different. The patients’ ROCs were lower than those of the controls, showing that hippocampal damage reduced the sensitivity of perception and/or working memory. However, the deficits were restricted primarily to the intermediate confidence responses (the middle points of the ROCs). Patients and controls performed similarly for the high-confidence old (“same”) responses (i.e., the leftmost points) and the high-confidence new (“different”) responses (i.e., the rightmost points). Estimates of recollection and familiarity indicated that the patients were impaired at making familiarity-based responses, whereas recollection responses were unaffected. Importantly, the selective familiarity impairments were observed in patients with selective hippocampal damage as well as those with more extensive MTL damage, indicating that in visual change detection, the hippocampus is critical in supporting familiarity. Importantly, in this study the two images were presented simultaneously, and the stimuli were quite complex. However, subsequent studies indicated that the results generalize to conditions using brief delays and much simpler stimuli as well.

For example, similar effects were observed in a study that examined memory for colored squares (Figure 4b; Goodrich, 2017). Participants studied a small set of items for 300ms followed by a 1s blank screen, then they were presented with a test array that could either

be identical to the study array or had one item presented in a different color. The target item was highlighted with a box and participants made a confidence judgment to indicate if that item was the same or different. In one block of trials only 7 canonical colors were used and the study array included 5 items, whereas in another block of trials a full range of colors were used and the study array included only 3 items. The results were comparable in the two conditions and as such collapsed. Consistent with the results from the earlier study with scenes, the amnesics' ROCs were lower than the controls, indicating that working memory accuracy was reduced in the patients, and again the deficits were limited primarily to the intermediate confidence responses (i.e., the middle of the ROCs). Parameter estimates from the ROCs confirmed that the patients did not exhibit deficits in recollection, but they were impaired at making familiarity-based responses.

The same pattern of results was also observed in a subsequent study in which participants only had to remember a single complex Gabor (Figure 4c; Goodrich, et al., 2019). On each trial participants studied a colored Gabor for 400ms followed by a 1s delay, and then were presented with a test item that was either the same or different from the study item (i.e., the spatial frequency, color or location of the item may have changed). As with the earlier studies, amnesics were impaired relative to controls; this impairment was limited to the intermediate confidence responses; and this resulted in a reduction in familiarity rather than recollection.

Results from a related neuroimaging study converge in showing that the hippocampus supports familiarity rather than recollection-based responses in change detection tasks (Aly et al., 2013; Aly et al., 2014). Participants were presented with a scene that was followed by a noise mask and then a scene that was either identical or globally changed (pinched or expanded as in the patient study described above). Hippocampal activity increased linearly with familiarity confidence ratings and did not increase further for the highest-confidence responses (see lower right panel in Figure 3). Similar familiarity-related activity was observed in the parahippocampal cortex and ventral temporal cortex. Further, hippocampal functional connectivity with occipitotemporal regions increased with increasing familiarity strength. These results suggest that the hippocampus interacts with regions in the ventral visual stream to support familiarity-based responses across short delays in perception and/or working memory. In contrast, recollection was related to activity in the lateral and medial parietal cortex: these regions responded differentially for high-confidence responses but did not track changes in familiarity strength (Aly et al., 2014). (see lower left panel of Figure 3). These results are consistent with earlier studies linking parietal and frontal attentional networks to the active maintenance of items in working memory (Corbetta, 1998; Miller et al., 1996; Naghavi & Nyberg, 2005; Ptak, 2012; Ungerleider, 2000), as well as studies linking these regions to trials in which participants have conscious access to detailed mnemonic information (Dehaene et al., 2006; Naghavi & Nyberg, 2005).

The patient and neuroimaging studies therefore converge in showing that in working memory and perception tasks the hippocampus supports intermediate confidence familiarity-based recognition responses and does not appear to be involved in high confidence recollection-based responses. Rather, recollection was associated with activity in the

parietal cortex. The latter results are consistent with prior work linking working memory maintenance and conscious experience with frontoparietal attentional networks.

Criterion-based process-masking in working memory.

The data reviewed above indicate that hippocampal damage leads to deficits in visual discrimination tasks even if the delay interval is very short or stimuli are presented simultaneously. These results are surprising given that some previous studies have shown that working memory is not compromised in patients with hippocampal damage (e.g., Jeneson et al., 2012; Baddeley et al., 2011). However, the ROCs indicate that the ability to detect this deficit is critically dependent on the particular response bias that the participants adopt, and so a failure to measure both accuracy and response bias could mask these impairments (i.e., ‘criterion-based process-masking’). For example, consider a scenario in which participants adopt a strict response criterion: they respond ‘old’ (or ‘same’) only if they are sure the test item is identical to the study item, or conversely, they respond ‘new’ (or ‘different’) only if they are sure the test item is different from the study item. This would lead to performance at the leftmost or rightmost points on the observed ROCs in Figure 4, respectively. At these end points of the ROCs the patients were not impaired relative to controls. It was only when one examines intermediate confidence responses that the deficits become apparent (i.e., the middle of the ROC). Thus, if participants in a working memory study adopt a strict response criterion such that they are relying primarily on recollection then amnesic patients will not be impaired, but if they adopt an intermediate response criterion they will make use of both recollection and familiarity, and so the patients will be impaired. This could explain why some previous studies that have examined only old/new recognition responses have failed to find significant impairments in working memory tests in amnesic patients (Jeneson et al., 2012; Baddeley et al., 2011). Although it is difficult to determine if criterion-based process-masking occurred in these previous studies, the current results point to the importance of using methods such as ROC analysis when examining the role of the hippocampus in working memory.

Importantly, these process masking artifacts in working memory are not avoided by applying statistical measures of memory accuracy such as ‘*proportion correct*’ or *d'* to old/new recognition data. Although these are often thought of as providing a way of measuring sensitivity in a way that is unbiased by response criterion, both make strong assumptions about the shape of the observed ROCs (Hautus et al., 2021), and they do not overcome these masking artifacts. For example, calculating the *proportion correct* or *d'* leads to the same problems whereby when adopting a strict criterion the resulting accuracy measures are not different between patients and controls, whereas the patients are impaired at the intermediate confidence levels (Goodrich & Yonelinas, 2016).

The role of the MTL in detecting global vs. discrete changes in working memory for novel objects.

The existing working memory ROC results suggest that amnesic patients are able to actively maintain specific items from the study event (i.e., recollection) at a normal level, but that they exhibit deficits in familiarity-based working memory discriminations. These results have been interpreted as indicating that the hippocampus supports a global matching signal

that indicates how well the test stimulus matches the immediately preceding study event (Aly et al., 2013; Yonelinas, 2023). Evidence that the familiarity signal in perception and working memory reflects global visual matching information comes from earlier behavioral studies (Aly & Yonelinas, 2012). For example, ROC experiments showed that the detection of global scene changes (i.e., scenes were pinched or expanded) was supported by high levels of familiarity and lower levels of recollection relative to the detection of discrete scene changes (i.e., the appearance or disappearance of objects) — which were associated with lower levels of familiarity and higher levels of recollection (Aly & Yonelinas, 2012). In addition, high confidence responses were related to subjective reports akin to ‘remembering’ (i.e., becoming aware of the specific change), whereas intermediate confidence responses were associated with reports of sensing (i.e., knowing that a change had occurred but being unable to identify what aspect had changed). Moreover, only for the high-confidence judgments were participants able to accurately report the specific visual change that was made. Thus, the working memory responses that are disrupted in amnesic patients appear to be the familiarity responses that rely on a global visual match signal, rather than high-confidence ‘recollection’ responses whereby specific details of the study event are reported.

An additional test of the claim that the hippocampus supports familiarity rather than recollection in working memory is to examine whether amnesics are preferentially impaired in working memory tests that require the detection of global visual changes compared those that require the detection of discrete local changes. That is, if the hippocampus is truly critical in detecting global visual changes in working memory whereas other cortical regions are sufficient to support the maintenance and recollection of discrete objects, then amnesic patients should be particularly impaired in working memory tests in which the changes are global in nature compared to when those changes are discrete. Alternatively, amnesics may exhibit deficits in familiarity-based working memory regardless of the global/discrete nature of the changes. As far as we are aware this has never been directly tested. In the experiment described next we examined the effects of hippocampal amnesia on working memory for complex objects that require either the detection of discrete or global changes. Participants were presented with complex objects that were identical or changed either in a global manner (i.e., the images were pinched or expanded as in the study of scenes by Aly et al., 2013), or a discrete manner such that specific features were altered (see Figure 5). In both conditions, participants made same/different confidence judgments so that ROC shape could be assessed to determine if the patients’ deficits were greater for the global compared to the discrete changes. In addition, we use the ROCs to derive estimates of recollection and familiarity, to determine if any observed deficits are due to reductions in familiarity, as has been observed in the previous studies.

Participants—Seven neurological amnesic patients (three male, four female, M=42 years) with an average of 17 years of education participated in the study. Three patients had damage limited to the hippocampus, while four patients had damage to the hippocampus and surrounding MTL cortex. The average patient IQ was 108, as measured by the Shipley Institute of Living Scale (SILS), and patients scored, on average, in the 15th percentile on the Doors and People memory battery. Average patient z-scores for all subtests, except the attention index, of the Wechsler Memory Scale-Revised (WMS-R) were

more than one standard deviation below the average control z-scores. Demographics and neuropsychological scores for the patients and controls are shown in Table 1.

Patient 1001 suffered from Hashimoto encephalopathy and exhibited abnormal necrotic cavities on the left hippocampus and similar but less pronounced cavities on the right hippocampus. Patient 1002 suffered from adult-onset pediatric autoimmune neuropsychiatric disorders associated with streptococcal infections (PANDAS) encephalopathy and exhibited abnormal necrotic cavities on the left and right hippocampi. Patients 1001 and 1002 had cavities with a rounded shape that resembled pathologic cavities described in specimens of hypoxia-related CA1 necrosis (Nakada et al., 2005). The extent of damage was determined from the patients' MRI scans, and there was no apparent damage in the surrounding parahippocampal gyri. Patient 1003 had limbic encephalitis, and MRI scans suggested damage limited to the hippocampus bilaterally with no damage apparent in the surrounding parahippocampal gyrus. Grey matter volume estimates indicated that the left and right hippocampi were reduced in volume, but no other MTL structure showed significant volume reduction. See Aly et al., 2013 for estimates of grey matter volume for this patient (referenced as Patient 2). Patient 1005 had damage to the hippocampus and surrounding parahippocampal gyrus bilaterally following a traumatic brain injury due to a car accident. The extent of damage was determined from the patient's high-resolution MRI scan. See (Kolarik et al., 2016) for estimates of grey matter volume for this patient. Patient 1006 suffered a traumatic brain injury due to a car accident, resulting in a hypoxic event and selective hippocampal damage. Clinical scans appeared normal with the exception of volume reductions in the hippocampus. Grey matter volume estimates indicated that both the left and right hippocampi were reduced in volume, but no other MTL structures showed significant volume reduction. See Aly et al., 2013 for estimates of grey matter volume for this patient (referenced as Patient 1). Patient 1007 had viral encephalitis, resulting in encephalomalacia and extensive volume loss in the right temporal lobe, right hippocampus and surrounding parahippocampal gyrus, and right orbitofrontal cortex. The extent of damage was determined from the patient's MRI scan. Patient 1009 had a left temporal lobectomy to treat epilepsy. The surgery was a standard left anterior temporal lobe resection, in which approximately 4 cm of the anterior temporal lobe, including the anterior half of the hippocampus, the amygdala, and the anterior third of the parahippocampal gyrus, were removed. The rest of the brain appeared to be normal on a high-resolution MRI scan.

Fourteen healthy controls (five male, nine female, $M=43$ years) with an average of 17 years of education participated in the study. None of the controls had any history of psychological or neuropsychological disorders and all performed normally on neuropsychological tests. The average control IQ was 112 and controls scored, on average, in the 67th percentile on the Doors and People memory battery. The patient and control groups were matched with respect to age, education, and estimated IQ. The study was approved by the University of California, Davis Institutional Review Board and informed consent was obtained from all participants prior to testing. Participants were compensated \$15/hr for their time.

Materials—Two hundred and forty colored fribbles (Barry et al., 2014) served as experimental stimuli, and an additional sixteen were used for practice. For each stimulus, altered versions were created in Adobe Photoshop (see Figure 5). For the global

manipulation, one image was expanded outward slightly using the “spherize” option and the second was contracted inward slightly using the “pinch” option. For the discrete manipulation one of the object features (i.e., head, neck, legs or tail) was altered.

Procedures—On each trial, participants viewed a fixation screen for 1.5 s, followed by the first object for 500ms, which was followed by a 50ms noise mask, and then the second object for 500ms. This was then replaced with a 1–6 confidence scale for a self-paced same/different judgment: 1 = sure different, 2 = maybe different, 3 = guess different, 4 = guess same, 5 = maybe same, 6 = sure same. The experiment consisted of a block of 120 discrete change trials followed by a block of 120 global change trials. A pilot study indicated that test order did not impact the observed ROCs and so to reduce variability across patients the same test order was used for all participants. Practice trials were presented at the beginning of each block to familiarize participants with the types of changes that could be expected. In each block sixty trials were “same” trials in which identical stimuli were presented, and sixty trials were “different” trials in which one of the items was altered. Two stimulus lists were created so that each stimulus was tested on both “same” and “different” trials across participants. Same and different trials were presented in a random order. Each stimulus was trial unique such that it was presented only once in either the discrete or global condition.

Results—Figure 5 presents working memory ROCs for the patients and controls for the global and discrete change conditions, and individual measures of sensitivity and process estimates are presented in Table 1. Figure 5 indicates that the amnesic patients were impaired at detecting global changes (i.e., their ROCs were lower than those of the controls), whereas they were relatively unimpaired detecting discrete changes (i.e., the ROCs overlapped). Perceptual sensitivity was quantified by calculating the area under the curve (AUC). There was a significant effect of group ($F(1, 38) = 6.627, p < 0.05$) indicating that working memory sensitivity was significantly reduced in the patients relative to the controls. The group by condition interaction failed to reach the level of significance ($F(1, 38) = 3.037, p = 0.09$); however, planned directional contrasts indicated that the patients were impaired in the global condition (.65 vs .77, $t(19) = 2.583, p < .01$), but they were not significantly impaired in the discrete condition (.71 vs .73, $t(19) = 0.7571, p > .05$). The current patient sample ($N=7$) was not sufficient to support an examination of subgroup differences, but consistent with previous work (Aly, 2011) a large majority of the patients performed below average, and the impairment was numerically larger in the patients with more extensive damage. Note that there was no significant effect of condition ($F < 1$), indicating that overall performance, across groups, was comparable in the discrete and global test conditions.

An examination of parameter estimates (see Table 1) showed that for familiarity there was a significant effect of group ($F(1, 38) = 4.179, p < 0.05$), indicating that familiarity was significantly reduced in the patients relative to the controls. The group by condition interaction failed to reach the level of significance ($F(1, 38) = 1.153, p = 0.30$), but planned directional contrasts indicated that the patients showed familiarity impairments in the global condition (0.41 vs 0.83, $t(19) = 1.841, p < .05$), but not in the discrete condition (0.49 vs 0.62, $t(19) = 0.912, p > .05$). An examination of recollection estimates indicated that there was no overall effect of group or of condition ($ps > .1$), but there was a group by condition

interaction ($F(1,38) = 4.179, p < 0.05$). Planned contrasts indicated that recollection was lower in the patients than controls in the global condition (0.29 vs 0.14, $t(19) = 2.4258, p < 0.05$), but not in the discrete condition (0.24 vs 0.26, $t(19) = 0.440, p = 0.67$).

Discussion

The amnesic patients were significantly impaired at detecting global changes in a working memory test for novel objects, whereas they performed in the normal range when detecting discrete changes. Importantly, controls' performance was similar in the discrete and global change conditions indicating that the patient impairments were not due to differences in overall difficulty of the tests, but rather were due to the global/discrete nature of the changes.

The results provide support for the claim that the medial temporal lobe supports a global familiarity matching process in visual perception and working memory, and are in agreement with a previous study that found that patients were impaired in visual discrimination of scenes in which the changes were global in nature (Aly et al., 2013). The results are also broadly consistent with studies showing that in perceptual discrimination tasks, patients are not impaired at making judgments about simple discrete feature changes such as color or objects whereas they are impaired when the task requires the detection of relational or configural changes such as alterations of spatial configurations (A. C. H. Lee et al., 2005; A. C. Lee & Rudebeck, 2010; Ruiz et al., 2020). Together these results indicate that the MTL plays a particularly important role in working memory and perception when the tasks rely on detecting global rather than discrete changes to the visual stimuli.

The differences observed between the global and discrete change conditions are consistent with a growing body of research showing that working memory decisions can be based either on discrete item information (e.g., memory for a particular red square), or on global scene statistics (e.g., the individual squares formed an coherent overall pattern) (Brady & Alvarez, 2011, 2015). Although this work has not focused on the role of different brain regions, the current results suggest that these two types of working memory discriminations may differentially depend on the hippocampus. The results are also broadly consistent with prior studies showing that hippocampal patients are particularly impaired in working memory and perception tasks that involve scene processing (e.g., A. C. H. Lee et al., 2005; A. C. Lee & Rudebeck, 2010; Maguire & Mullally, 2013). To the extent that scene processing generally requires the processing of global spatial information one might expect to observe more pronounced deficits for scenes than for other types of materials. However, the work we discussed above shows that the observed deficits are not limited to studies of scenes, but rather they generalize to studies of novel objects, colored squares and even gabor.

The impairment in detecting global changes was observed in patients with selective hippocampal lesions as well as those with more extensive MTL damage, suggesting that the hippocampus is critical in supporting working memory for global object changes. These results are consistent with previous work indicating that damage to the hippocampus is sufficient to disrupt working memory and perceptual sensitivity (Aly et al., 2013; Goodrich et al., 2019; Goodrich & Yonelinas, 2016). In addition, estimates of recollection and

familiarity revealed that the patient deficits in working memory sensitivity for objects in the global change condition were due in part to significant reductions in familiarity. The familiarity deficit in working memory is consistent with earlier work using similar test procedures that had indicated selective familiarity decreases in change detection for scenes (Aly et al., 2013), sets of colored squares (Goodrich & Yonelinas, 2016), and complex gabor (Goodrich et al., 2019). However, unlike those earlier studies in which recollection estimates were unaffected in the patients, in the current study recollection was significantly lower in the patients than the controls. Why did both recollection and familiarity decrease in the patients in the current study? One possibility is that recollection decreased because some of the patients suffered from undetected damage to regions outside the hippocampus. Although it is impossible to rule out, the recollection impairments were as apparent in the patients with selective hippocampal damage as much as those with documented damage outside the hippocampus, which argues against this account. A more likely possibility is that the reduction in recollection observed in the current study may be due to the novel nature of objects used in the current study. The prior studies that have reported selective familiarity impairments in working memory have examined more common materials like colored squares and scenes, whereas in the current study we examined novel artificial objects that the participants have not had prior experience with. Evidence that the hippocampus plays a particularly important role in processing novel materials comes from studies showing that working memory impairments in hippocampal patients are more pronounced for nonwords and non-famous faces than for words or famous faces (Rose et al., 2012; for convergent fMRI results see Ranganath & D'Esposito, 2001). The result suggests that in working memory tests for novel materials, the hippocampus may support not only a global familiarity matching signal but it may also provide specific recollective information as well. We acknowledge however, that this account of the recollection impairment is post hoc, and the effect has only been observed in this one experiment. Moreover, the patient sample size was rather limited, as is fairly common in studies of special populations like hippocampal lesion patients. Future studies directly contrasting working memory impairments in recollection and familiarity for familiar and novel materials, with larger samples, will be useful in testing this possibility further.

In sum, the experiment joins previous work indicating that the hippocampus plays a critical role in visual working memory, and further indicates that its role is particularly noticeable when the changes involve global rather than discrete changes in the materials. In addition, it joins prior work indicating that medial temporal lobe damage disrupts familiarity-based working memory judgments, but further suggests that for novel materials both recollection and familiarity may be impaired.

Neurocomputational models of episodic and working memory.

Why does the hippocampus support recollection in episodic memory, whereas it supports familiarity in working memory? One possibility is that the basic computation supported by the hippocampus is fundamentally different in working memory and episodic memory tests. Although it is certainly possible that participants may adopt different encoding or retrieval strategies in these two types of tests, we suspect that the computation supported by the hippocampus remains largely the same in these two types of tests, and that the observed

differences in the role that the hippocampus plays in these tests reflects the different task demands (Aly & Turk-Browne, 2018; Elfman et al., 2014).

In support of this possibility, a neurocomputational model of the medial temporal lobes that has been found to provide a good account of episodic recognition (i.e., the Complementary Learning Systems or CLS model) also naturally produces the observed recollection and familiarity effects for both episodic and working memory (Elfman et al., 2014). The model assumes that in episodic memory recollection relies on a hippocampal pattern completion process, whereas familiarity relies on a cortical matching process (Elfman et al., 2014; Elfman & Yonelinas, 2015; McClelland et al., 2020; Norman & O'Reilly, 2003; Parks et al., 2011). This model is motivated by known anatomical and physiological properties of the hippocampal subfields and the surrounding cortex, and it naturally produces a thresholded hippocampal recollection signal and a strength-like familiarity signal as has been observed in tests of episodic memory. The model assumes that when a study episode occurs, the hippocampus receives information about the item and the encoding context via the entorhinal cortex, and it assigns each episode a relatively nonoverlapping representation in the dentate gyrus (DG) and region CA3. The nonoverlapping representations arise because of the sparse levels of activity in DG and high levels of lateral inhibition in CA3. Active units in CA3 are linked to one another and to a copy of the input pattern in CA1. In this way, at time of test, if a partial version of the study episode is presented as a retrieval cue, this leads to the pattern completion of the original memory. Importantly, however, pattern completion occurs for only some of the study items, and it fails to occur for others (see strength distributions in the upper left panel of Figure 3). This produces a thresholded/bimodal recollection strength output in CA1 and the entorhinal cortex, with some proportion of old items leading to recollection, and the remainder producing only very low levels of activity that is similar to that produced by nonstudied items. In this way, items that are recollected (i.e., pattern completed) are highly diagnostic of having been studied and so support highly confident recognition responses.

In contrast, familiarity in tests of episodic memory is assumed to depend on cortical associative networks that are reliant on Hebbian learning and inhibitory competition. The idea is that units or networks of cells in the cortex surrounding the hippocampus compete to encode (via Hebbian learning) regularities that are present in the study events by altering the connectivity between units. In this way, at time of test, items that have been previously encoded will tend to have sharper representations than new items. That is, new items will weakly activate many units whereas studied items will strongly activate a relatively small number of units. Thus, unlike the hippocampus—which leads to the pattern completion of associated episodic details—the cortex provides a signal of stimulus familiarity (see the strength distributions in the upper right panel in Figure 3). Because the familiarity distributions for old and new items are overlapping, there is no threshold above which familiarity occurs; rather familiarity varies continuously and so increases in familiarity should be continuously related to increases in recognition confidence.

Although the CLS model was not explicitly designed to account for perception or working memory, subsequent model simulations have indicated that the hippocampal component of the model can support perception and/or working memory, and in addition that it does

so by producing a signal detection like global matching signal that is in agreement with the working memory ROC results (Elfman et al., 2014). That is, using the same model parameters that are used to account for episodic memory, when the task involves a single image followed by a repeated image or by a slightly changed image, the model pattern-completes for both types of items (because the test item was presented immediately after the study item), but it matches studied items slightly more strongly than changed items (see strength distributions in lower right panel of Figure 3), thus it produces a signal detection like global matching signal.

If the hippocampus supports familiarity-based discriminations in working memory then what supports recollection in these tests? The existing ROC results from hippocampal lesion patients indicate that it must be some set of regions outside the hippocampus (Aly et al., 2013, 2014; Goodrich et al., 2019; Goodrich & Yonelinas, 2016), and a number of findings indicate that the lateral parietal cortex appears to be particularly critical. For example, lateral parietal lesions lead to recognition deficits in both verbal and visual working memory (Berryhill et al., 2011; Mackey et al., 2016; Olson & Berryhill, 2009), and functional neuroimaging studies also implicate the lateral parietal cortex in studies of working memory (Buchsbaum et al., 2011; Chein et al., 2003). In addition, lateral parietal cortex activity is related to high-confidence change detection but does not track changes in lower confidence levels, indicating that the parietal lobe is involved in recollection-like visual perception and/or working memory (Aly et al., 2013, 2014).

These results are broadly consistent with a variety of ‘frontoparietal’ maintenance models of working memory, in which only a limited number of items can be maintained in an active state or can be held in a limited working memory buffer (Baddeley & Hitch, 1974; Chai et al., 2018; Cowan, 2001; Cowan et al., 2012; Curtis & D’Esposito, 2003; Luck & Vogel, 2013; Naghavi & Nyberg, 2005; Owen et al., 2005). In these models, a frontoparietal network is thought to be critical for actively maintaining representations in a form that is accessible to conscious awareness (Baars, 2005; Dehaene et al., 2006; Lamme, 2003; Naghavi & Nyberg, 2005), either by maintaining sustained activity (J. Fuster, 2015; J. M. Fuster & Alexander, 1971) or by coordinating oscillatory activity between the sensory regions responsible for processing the studied information (Luck & Vogel, 2013; Miller et al., 2018; Salazar et al., 2012).

Thus, the current proposal is that in working memory tests, performance relies on recollection of specific details of the study event - a process that is dependent on a frontoparietal maintenance process - but if that fails, participants can rely on a hippocampal global familiarity matching process. In contrast, in episodic memory the maintenance process will no longer support recollection - presumably because of the large number of intervening items and the long delay - and so performance will rely critically on the thresholded hippocampal pattern-completion process, and if this fails, performance can rely on a cortical familiarity matching process.

The proposed framework provides a way of thinking about how working memory and episodic memory may be related, but it is far from complete, and it opens up a number of important questions that will need to be addressed in future studies. First, the approach

focuses on only a small subset of brain areas, and it will be critical to determine which subregions within these broader areas give rise to these memory processes, and how these regions interact with other cortical and subcortical regions. For example, posterior regions in the lateral parietal lobe are involved in both verbal and visual WM whereas more inferior parietal regions as well as inferior temporal regions can be more material specific (Chai et al., 2018; Ranganath et al., 2004; Ravizza et al., 2011). Work will be needed to determine how these different subregions are related to recollection and familiarity-based WM discriminations for both visual and nonvisual materials. Second, the model assumes that the hippocampus provides a familiarity signal that is useful in supporting working memory, but it seems quite likely that there are other familiarity strength signals that can also support working memory. For example, familiarity-related signals have been observed in the hippocampus as well as in regions along the ventral stream such as the lateral occipital cortex, the fusiform gyrus, and the parahippocampal cortex (Aly et al., 2013, 2014), suggesting that these earlier visual regions may also provide strength signals that could be useful in supporting working memory discriminations. Moreover, the current results indicate that over very brief delays the hippocampus provides a global matching signal, but under longer delays the manner in which it contributes to performance is unclear. For example, the hippocampus can play an increasingly important role in working memory tasks as the study-test delay increases much beyond one second (e.g., Jeneson et al., 2012). Whether the hippocampus is contributing to WM at these longer delays by supporting a strength or thresholded signal is currently unknown. In addition, in the working memory study for fribbles reported above, the patients exhibited a reduction in recollection as well as in familiarity, suggesting that at least with novel materials hippocampally-based recollection may contribute to memory even at very short delays. Thus, future work that examines the role of recollection and familiarity in working memory for a variety of different materials and delay periods should be particularly informative.

Conclusions

A large body of research has shown the hippocampus supports recollection rather than familiarity in episodic memory tests; these results are well documented and probably not particularly controversial for most readers. However, an emerging body of work suggests that the hippocampus supports familiarity in working memory, a conclusion that is likely to be seen as much more controversial. We believe that the conclusion is supported by several important observations: i) ROC analysis across several patient studies indicates that hippocampal damage primarily disrupts working memory accuracy across intermediate confidence responses consistent with a reduction in a memory strength signal, rather than disrupting high confidence responses arising from the recollection of specific study details. ii) Parameter estimates based on a dual process model of the observed ROCs further verifies that amnesics exhibit a deficit in the strength-based signal detection component of ROCs (i.e., familiarity). iii) The intermediate-confidence responses that are impaired in amnesics are phenomenologically experienced as sensing or knowing that a change has occurred whereas the high confidence responses that are unaffected in amnesia are experienced similarly to remembering, such that participants are consciously aware of what has changed and can accurately report that specific information (e.g., Aly & Yonelinas,

2012). iv) In the current study that examined working memory for novel objects, amnesics were impaired when required to detect global changes, which was expected to rely heavily on familiarity-based signals, whereas they were unimpaired in detecting discrete changes, which was expected to rely on recollection-based signals (based on our past behavioral work, Aly & Yonelinas, 2012). v) Neurocomputational models of the medial temporal lobes are consistent in showing that although the hippocampus supports a recollection process in episodic memory, in working memory tests it supports a familiarity signal (Elfman, Aly, & Yonelinas, 2014). These results indicate that the hippocampus contributes to working memory not by supporting short term recollection, but by contributing a functionally and phenomenologically distinct memory signal that tracks global visual changes.

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Figure 1. Illustrations of episodic and working memory tests.

In episodic memory tests (left panel), a series of items (e.g., pictures, words, letters, colors, etc.) are presented for participants to encode. Following a delay period that can range from tens of seconds to hours, days, or even longer, participants are presented with a mixture of studied and nonstudied items and must indicate if each item was old or new using a confidence scale. In working memory tests (right panel), a single item (or small number of items such as colored squares) is briefly presented; following a brief delay (on the order of seconds), participants are presented with an old or a slightly modified new item (i.e., a scene may be modified or the color of an item may change) and they are required to indicate if the item was old or new using a confidence scale.

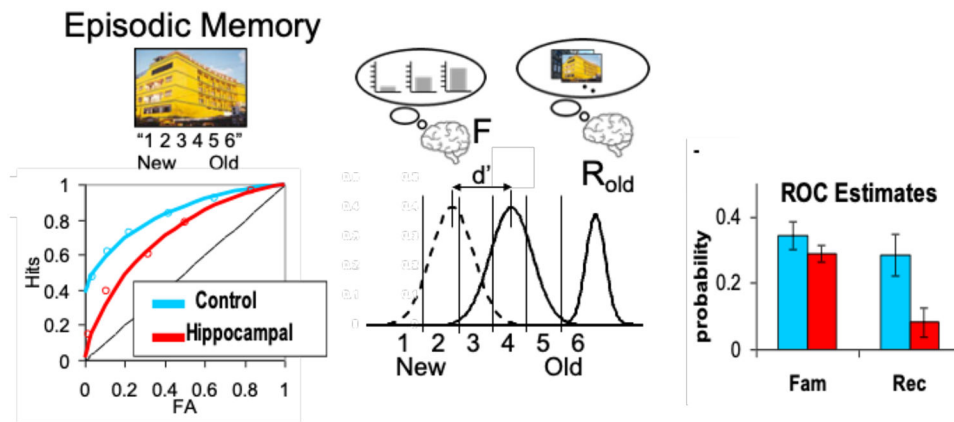


Figure 2. An illustration of the effects of hippocampal amnesia on recollection (R) and familiarity (F) in episodic recognition memory.

Recognition confidence ROCs for amnesics and controls (left panel), a dual process signal detection model (central panel), and parameter estimates of recollection and familiarity (right panel). Recognition memory is impaired in the amnesics due to a reduction in high confidence recognition responses (i.e., left portion of the ROCs, and the rightmost distribution in the model), corresponding to a selective reduction in recollection estimates. The results are from Yonelinas et al., (2002) which examined the effects of mild hypoxia on memory confidence ROCs for words, but the same pattern has been observed across a wide range of materials using several different experimental methods such as remember/know, process dissociation and structural equation modeling, in a variety of patient groups with selective hippocampal damage as well as in rodents with selective hippocampal lesions (see main text).

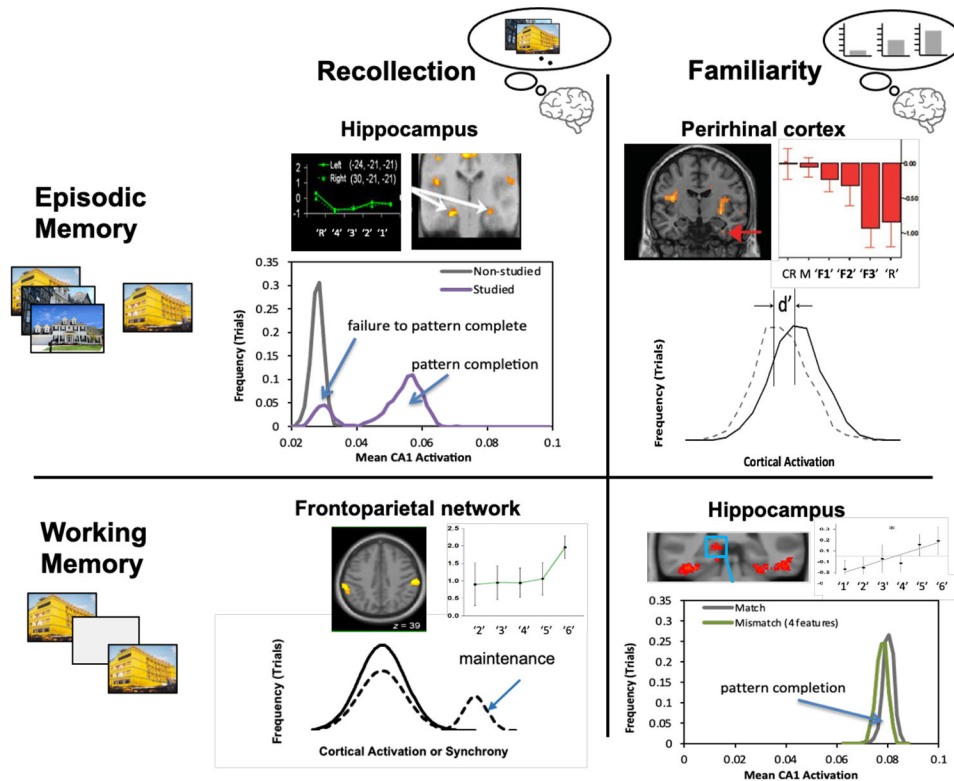


Figure 3. Hippocampal and cortical regions implicated in recollection and familiarity in working memory and episodic memory.

The hippocampus forms complex representations that bind together the various aspects of each study event. In tests of episodic memory (upper left panel), a retrieval cue is presented which leads to successful pattern completion in the hippocampus for some studied items, but not for others, leading to a thresholded/bimodal memory signal and increased hippocampal activity for recollected compared to non-recollected items. In contrast, familiarity (upper right panel) is dependent on cortical networks in the perirhinal cortex that are sensitive to repetition which leads to a shift in the level of activity for old compared to new items, consistent with a signal detection process, and to changes in perirhinal activity that track judgements of familiarity strength. In working memory tests (lower right panel), because there is no significant delay or intervening items, the hippocampus successfully pattern completes for both old and new items producing a signal detection like global match signal that is stronger for old items (matched) than new items (mismatched). Thus, hippocampal activity increases gradually with familiarity strength. In addition to the hippocampal signal, working memory can be supported by a fronto-parietal maintenance process (lower left panel) whereby a limited set of items or objects are held in an active state via increased firing or synchronous interleaved firing across sensory cortical regions, which supports a thresholded cortical recollection signal in regions including the supramarginal gyrus. Simulation results and illustrative fMRI results are from Aly et al., (2013,14), Elfman et al., (2014), Montaldi et al., (2006), and Yonelinas et al., (2005).

Working memory

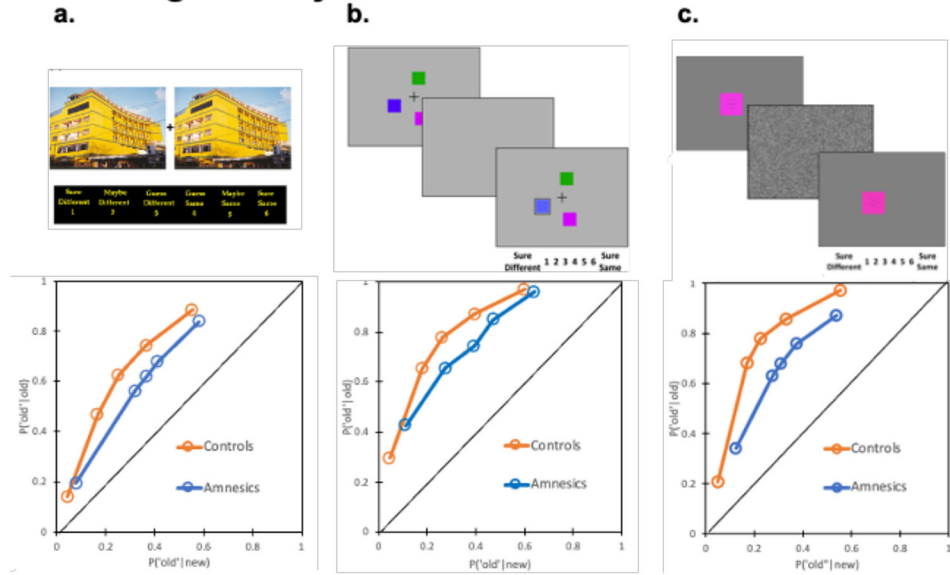


Figure 4. The effects of hippocampal amnesia on working memory and perception.

Amnesic patients are impaired in change detection discriminations for a) scenes (Aly, Ranganath & Yonelinas, 2013), b) colors (Goodrich & Yonelinas, 2016), and c) complex gabors (Goodrich, Baer, Quent & Yonelinas, 2019). The patients are not impaired in making high confidence responses, but rather are impaired at the intermediate confidence responses (middle of the ROCs), corresponding to a selective impairment in familiarity.

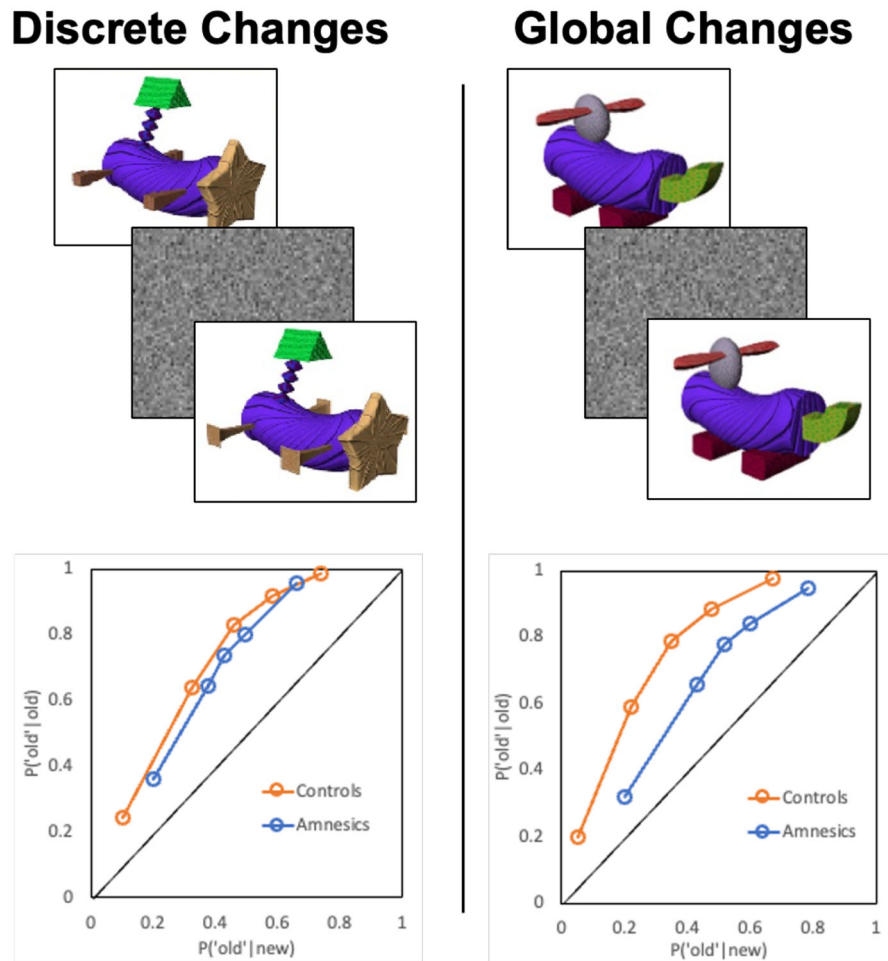


Figure 5. The effects of hippocampal amnesia on working memory for discrete and global changes.

Examples of novel objects that have been changed either globally by pinching/expanding the image (e.g., in the ‘Global Changes’ condition the second image has been slightly contracted in the center such that the grey oval appears to be slightly more elongated and the purple body appears narrower) or discretely by changing specific features (e.g., in the ‘Discrete Changes’ in the second image, the lower protruding joints have been changed to lighter brown with square endpoints). The bottom part of the figure shows the visual working memory ROCs for amnesics and controls in the discrete and global change conditions, indicating that the patients were impaired in detecting global but not discrete changes.

Table 1.

Participant characteristics and working memory measures*.

Patient ID	Damage	Age	Sex	Education	WMS-R z-score (Ver/Vis/Gen/Att/Del)	Doors and People %ile	Shipley IQ	AUC Discrete	AUC Global	Recollection Discrete	Recollection Global	Familiarity Discrete
1001	Bilateral HC	56	F	16	-0.9/-1/-1/1.3/-0.5	25	110	0.711	0.694	0.103	0.106	0.708
1002	Bilateral HC	31	F	18	-1.5/-1/-1.5/-0.5/-0.8	10	110	0.735	0.778	0.223	0.000	0.852
1003	Bilateral HC	62	F	12	-1.8/-0.3/-1.5/0.1/-2.2	1	112	0.703	0.682	0.385	0.281	0.049
1005	Bilateral MTL	30	F	19	-0.1/1.1/0.3/0.3/-0.4	5	110	0.694	0.546	0.246	0.000	0.408
1006	Bilateral MTL	33	M	17	-1.3/0.3/-0.9/0.2/-2.1	1	110	0.766	0.586	0.330	0.000	0.677
1007	R MTL	43	M	18	0.8/-0.9/0.1/1.2/-0.1	10	106	0.551	0.668	0.099	0.173	0.000
1009	L MTL	40	M	17	-1.6/0.4/-1.1/-0.7/-0.6	50	97	0.810	0.622	0.372	0.283	0.961
Amnesics	-	42.1	4 F 3 M	16.7	-0.9/-0.2/-0.8/0.3/-1	14.6	107.9	0.710	0.654	0.251	0.120	0.522
(N = 7)		(12.6)		(2.3)	(0.9/0.8/0.7/0.8/0.8)	(17.6)	(5.1)					
Controls	-	43.3	9 F 5 M	17.3	0.4/1.3/0.7/0.5/0.9	66.8	111.9	0.732	0.769	0.231	0.266	0.653
(N = 14)		(13.2)		(2.5)	(1.0/0.8/0.9/0.8/0.9)	(22.8)	(6.1)					

* Note. Individual scores are presented for each patient, followed by patient and control group means (standard deviations in parentheses). Abbreviations: HC = hippocampus; MTL = medial temporal lobe.