Pre-experimental Familiarization Increases Hippocampal Activity for Both Targets and Lures in Recognition Memory: An fMRI Study

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Abstract

In the present study, items pre-exposed in a familiarization series were included in a list discrimination task to manipulate memory strength. At test, participants were required to discriminate strong targets and strong lures from weak targets and new lures. This resulted in a concordant pattern of increased “old” responses to strong targets and lures. Model estimates attributed this pattern to either equivalent increases in memory strength across the two types of items (unequal variance signal detection model) or equivalent increases in both familiarity and recollection (dual process signal detection [DPSD] model). Hippocampal activity associated with strong targets and lures showed equivalent increases compared with missed items. This remained the case when analyses were restricted to high-confidence responses considered by the DPSD model to reflect predominantly recollection. A similar pattern of activity was observed in parahippocampal cortex for high-confidence responses. The present results are incompatible with “noncriterial” or “false” recollection being reflected solely in inflated DPSD familiarity estimates and support a positive correlation between hippocampal activity and memory strength irrespective of the accuracy of list discrimination, consistent with the unequal variance signal detection model account.

INTRODUCTION

Recent fMRI studies investigating recognition memory have offered opposing interpretations of the differential hippocampal activity elicited by studied information. One interpretation proposed by dual process (DP) theorists is that hippocampal activity primarily reflects retrieval of contextual information associated with a study episode, a qualitatively distinct process termed “recollection” (Mandler, 1980). Evidence cited in favor of this interpretation comes from experiments comparing high confidence “old” or “remember” responses with correct rejections (CRs) of new items or misses/forgotten items (e.g., Diana, Yonelinas, & Ranganath, 2007; Brown & Aggleton, 2001). However, an alternate view attributes this activity simply to strong memories, with confidence ratings presumed to be a proxy for memory strength (e.g., Wais, Squire, & Wixted, 2010; Squire, Wixted, & Clark, 2007).

Source memory tasks have also been employed to elicit hippocampal activity in fMRI studies via contrasts of correct versus incorrect source judgments for items identified successfully as old, the activity typically being attributed to recollection (e.g., Eichenbaum, Yonelinas, & Ranganath, 2007). However, confidence ratings are invariably higher for old items that are accompanied by retrieval of correct source information; hence, the hippocampal activity observed may reflect a memory strength confound (see Squire et al., 2007). To test this hypothesis, Wais et al. (2010) restricted an analysis of source memory judgments to high-confidence old responses, finding increased hippocampal activity for both source correct and incorrect decisions relative to missed or forgotten items. They interpreted these results as indicating the hippocampus contributes to strong memories rather than to a qualitatively distinct process of recollection (see also Wais, 2011, for a similar demonstration with respect to hippocampal activity during associative recognition). In discussing their findings, Wais et al. (2010) acknowledged the possibility that high-confidence incorrect source decisions might also reflect “false” recollection. However, the authors considered this explanation less likely because of the increased activity they had also observed in perirhinal cortex for high-confidence incorrect source decisions. According to DP theorists, perirhinal cortex has a selective role in a process termed “familiarity,” described as knowing that an item has been encountered beforehand in the absence of contextual information (Eichenbaum et al., 2007; Brown & Aggleton, 2001). If the increased activity reflected false recollection, Wais et al. reasoned this would not be consistent with a selective role for perirhinal cortex in familiarity. However, it is worth noting that Yonelinas and Jacoby (1996) demonstrated that false or “noncriterial” recollection may be reflected in inflated familiarity estimates according to the dual process signal detection (DPSD) model.
We obtained results supporting a memory strength account of hippocampal activity in a recent fMRI study of item repetition in recognition memory (de Zubicaray, McMahon, Dennis, & Dunn, 2011). According to DP theory, contrasts of correctly identified old items encoded during focussed versus divided attention conditions should be analogous to contrasts of correct versus incorrect source decisions in terms of engaging recollection (e.g., Eichenbaum et al., 2007; Yonelinas, 2002). Retrieval-related activity in the posterior hippocampus was elevated for high-confidence old responses compared with misses, although this did not differ between attention conditions. Furthermore, retrieval-related hippocampal activity increased in a graded manner across correctly identified old items that had been presented once, twice, or four times at study during focussed versus divided attention conditions. Critically, the pattern of activity was consistent with estimates derived from the unequal variance signal detection model (UVSD) model (Dunn, 2004; Donaldson, 1996), and inconsistent with estimates of familiarity and recollection derived from the DPSD model (Yonelinas, 1994).

The aim of the present fMRI study was to further investigate memory strength effects in relation to hippocampal activity by using a list discrimination task in conjunction with item repetition. To this end, we employed an experimental paradigm that produces a concordant pattern of positive responses to targets and lures on the basis of a manipulation of items learned in different list contexts. The paradigm involves three phases; familiarization, study, and test. In the first pre-exposure phase, participants are presented with a list of items presented multiple times (the familiarization series). In the second phase, they learn a study list that contains items from the familiarization series in addition to novel items. In the third phase, they are required to endorse only items learned in the study list. A number of behavioral studies have shown that “old” responses to targets and lures increase as a function of familiarity frequency in this type of design (e.g., McCabe & Geraci, 2009; Greene, 1999; Chalmers & Humphreys, 1998; Dobbins, Kroll, Yonelinas, & Liu, 1998; Maddox & Estes, 1997).

We focused our investigation of hippocampal activity on pre-exposed, familiar (i.e., strong memory) items. If “old” responses involving correct versus incorrect attributions of a familiar item to the study list show differentially increased activity, then this result may be interpreted as supporting the operation of a qualitatively distinct process such as recollection, as memory strength should be equivalent for both targets and lures. However, if hippocampal activity is also elevated for old responses with incorrect attributions of familiar items to the study list, then this may be considered evidence in favor of a memory strength account or potentially false recollection (e.g., Eichenbaum et al., 2007; Yonelinas, 2002). If so, UVSD and DPSD model estimates should assist in clarifying which of these explanations is the more viable, an approach not adopted in the previous fMRI studies. In addition, we examined activity in the perirhinal and parahippocampal cortices following previous reports of activity in these medial-temporal lobe regions attributed to familiarity and/or recollection (e.g., Wais et al., 2010; Kirwan, Wixted, & Squire, 2008; Diana et al., 2007).

METHODS

Participants

Sixteen volunteers were recruited from among University of Queensland students and staff (11 women; mean age = 23 years, range = 20–33 years). All were right-handed native English speakers, with no history of neurologic or psychiatric disorder, substance dependence, or known hearing deficits. All had normal or corrected-to-normal vision. Written informed consent was obtained for all participants before participating, and the university medical research ethics committee approved the experimental protocol.

Materials

The critical stimuli comprised 160 high-frequency concrete nouns, all five letters in length, selected from the British National Corpus (Leech, Rayson, & Wilson, 2001; mean frequency per million = 120.60; SD = 93.92). These were assigned randomly to familiarization, study, and test lists across participants following previous studies (e.g., Greene, 1999; Chalmers & Humphreys, 1998; Dobbins et al., 1998; Maddox & Estes, 1997).

Procedure

Participants were instructed in both familiarization and study phases to study lists of words for an unspecified memory test (e.g., Greene, 1999; Chalmers & Humphreys, 1998, Experiments 1 and 2; Maddox & Estes, 1997). In the first (familiarization) phase before being positioned in the MRI system for scanning, participants were presented with a set of 80 words on a computer monitor, each presented four times. The participants were then positioned in the bore of the MRI system and, before scanning, presented with a set of 80 words, all presented once. Of these words, 40 (i.e., half) had been presented in the familiarization set outside the MRI system. All study words were presented for 800 msec followed by a blank screen with a SOA of 3000 msec. Words were presented in black font on a white background and projected using a BenQ SL705X projector (BenQ, Taipei, Taiwan) onto a screen at the foot of the bore of the MRI system that participants viewed through a mirror mounted on the head coil, subtending approximately 10° of visual arc.

Next, participants were administered an old/new recognition memory test for the fMRI experiment. Each test list comprised 160 words consisting of 40 words presented
in both the familiarization and study sets, 40 solely in the familiarization set, 40 solely in the study set, and 40 new (i.e., unstudied, unfamiliarized) words not presented previously in the experiment, all presented in pseudo-random order. To minimize study–test repetition lag variability, all studied words were presented in the same quarter of the test list as at study. Participants were instructed to respond “old” only to those words presented in the list they had studied in the bore of the MRI system. During each trial, a fixation point appeared on the screen for 600 msec, followed by the word for 2500 msec. Participants were instructed to withhold their response until the word disappeared from the screen. Next the categories “certainly new,” “probably new,” “probably old,” and “certainly old” were presented together, in a cross formation around the center of the screen for up to 2 sec, depending on the speed of their response. This served both as a prompt to respond and to indicate which button should be pressed for a given response. Participants responded by pressing one of four buttons corresponding to their decision on a similarly arranged response pad using their right hand. They were instructed to adopt response criteria that enabled them to use each of the categories more or less equally. The selected label changed color to red for 200 msec to provide response feedback, and a blank screen was presented for the remainder of the 2-sec period. Thus, each trial lasted for 5.1 sec.

**Image Acquisition and Analysis**

Imaging was performed with a Bruker Medspec 4T MRI system (Bruker, Erlangen, Germany) equipped with a transverse electromagnetic head coil for radiofrequency transmission and reception (Vaughan et al., 2002). Functional T2*-weighted images depicting BOLD contrast were acquired using a gradient-echo EPI sequence optimized for both image quality and noise reduction (matrix size = 64 × 64; voxels = 3.6 × 3.6 mm; repetition time = 2.11 sec; echo time = 30 msec; flip angle = 90°; McMahon, Pringle, Eastburn, & Maillet, 2004). Each image volume comprised 36 axial 3.5-mm slices (0.1-mm gap) for 400 images. The first five volumes were discarded to allow tissue magnetization to achieve steady state. Head movement was limited by foam padding within the head coil. A point-spread function mapping sequence was acquired before the functional acquisition to correct geometric distortions (Zaitsev, Hennig, & Speck, 2003). Following the functional acquisition, a 3-D T1-weighted image was acquired using a magnetization prepared rapid acquisition gradient-echo sequence (matrix = 256 × 256; voxels = 0.9 mm³).

Preprocessing and analysis were conducted with Statistical Parametric Mapping software (SPM8; Wellcome Department of Imaging Neuroscience, Queen Square, London, UK). Functional volumes were resampled using generalized interpolation to the acquisition of the middle slice in time to correct for the interleaved acquisition sequence, then realigned to the initial volume using the INRIAlign toolbox (Freire, Roche, & Mangin, 2002). A mean image was generated from the realigned series, and coregistered to the T1-weighted image. The T1-weighted image was subsequently segmented using the “New Segment” procedure in SPM8. The “DARTEL” toolbox (Ashburner, 2007) was then employed to create a custom group template from the gray and white matter images and individual flow fields that were used to normalize the realigned fMRI volumes to the Montreal Neurological Institute (MNI) atlas T1 template. The resulting images were resampled to 3 mm³ voxels and smoothed with an 8-mm FWHM isotropic Gaussian kernel. Global signal effects were then estimated and removed using a voxel-level linear model (Macey, Macey, Kumar, & Harper, 2004).

Statistical analyses were conducted according to a two-stage, mixed effects model. Trial types corresponding to hits (correct “old” responses), misses (incorrect “new” responses), false alarms (FA; incorrect “old” responses, and CRs (“new” responses) were defined according to test condition (familiarization and/or study set), as well as CRs and FAs to unstudied items (foils/lures) and trials on which a response was omitted. These were modeled as effects of interest with delta functions representing each onset, along with a nuisance regressor consisting of response onsets, and convolved with a synthetic hemodynamic response function and accompanying temporal and dispersion derivatives. Standard high (1/128 Hz) and low pass filtering with an autoregressive (AR1) model were applied. Parameter estimates were derived at the fixed effects level using the general linear model and tested using linear (t) contrasts. The relevant contrast images were next entered in group level repeated measures ANOVAs in which covariance components were estimated using a restricted maximum likelihood procedure to correct for non-sphericity (Friston et al., 2002), and significant effects subjected to planned voxel-wise t contrasts.

A priori ROIs for the parahippocampal cortex and hippocampus, and perirhinal cortex were defined in each hemisphere as explicit masks for the analyses using labeled probabilistic maps from the atlases provided by Shattuck et al. (2008) and Holdstock, Hocking, Notley, Devlin, and Price (2009), respectively. A height threshold of p < .005 was adopted following previous studies (e.g., Suzuki, Johnson, & Rugg, 2011; Diana, Yonelinas, & Ranganath, 2010) in conjunction with a corrected cluster (k) threshold of p < .05 estimated for each ROI using a Monte Carlo estimation procedure with 10,000 simulations (AlphaSim, implemented in Analysis of Functional Neuroimaging toolkit, National Institute of Mental Health, Bethesda, MD).

**RESULTS**

**Behavioral Data**

One participant scored below chance level for their list discriminations, and another failed to respond on approximately 50% of trials. Their data were excluded from
subsequent analyses. The overall hit rates (old responses involving correct attribution of an item to the study list) and FA rates (old responses involving incorrect attribution of an item to the study list) are displayed according to confidence rating in Table 1 as a function of familiarization and study.1 An ANOVA conducted on the mean old responses as above revealed significant effects of Familiarization, $F(1, 13) = 27.34, MSE = .055, p < .001$, $\eta^2 = .68$, and Study, $F(1, 13) = 11.85, MSE = .006, p < .005$, $\eta^2 = .48$, and no interaction $F(1, 13) = 0.76, MSE = .008, p = >.05$, $\eta^2 = .06$.

Familiar targets attracted a higher percentage of high-confidence “sure old” responses than targets presented solely in the study list (70% vs. 53%). This is consistent with both a memory strength account and a DP perspective, as recollection-based discrimination is considered to be reflected almost exclusively in high-confidence ratings (Yonelinas, 2002). However, this was also the case for high-confidence “sure old” responses for familiar relative to novel lures (66% vs. 27%), a result inconsistent with veridical recollection yet perhaps interpretable in terms of memory strength/familiarity. To address this issue, we first calculated receiver operating characteristic (ROC) curves (Figure 1). Inspection of the ROCs revealed them to be relatively linear, indicating participants had considerable difficulty discriminating pre-exposed items presented in the study list.

We next fit both UVSD (Dunn, 2004) and DPSD (Yonelinas, 1994) models to each participant’s full set of responses (across four response categories: certainly old, probably old, certainly new, probably new) separately using maximum likelihood estimation to estimate contributions of either memory strength or familiarity and recollection in the different memory conditions (Figure 2). A repeated measures ANOVA on the Memory Sensitivity ($d_m^2$) values derived from the UVSD model as within-subject variables revealed a significant main effect, $F(1, 13) = 9.8, MSE = .88, p < .001$. A similar ANOVA on the Variance Estimates ($\sigma^2$) revealed a marginally significant effect, $F(1, 13) = 2.84, MSE = .26, p = .077$. Paired $t$ tests on the $d_m^2$ values indicated there was no significant difference in memory strength between familiar targets and lures ($t[13] = 1.37, p = .2$), although both were significantly elevated compared with novel targets ($t[13] = 3.5, p < .005$ and $t[13] = 3.23, p < .05$, respectively). A similar pattern was observed for the variance estimates, although only familiar and novel targets differed significantly ($t[13] = 2.24, p < .05$). The DPSD familiarity estimates differed significantly between conditions $F(1, 13) = 11.36, MSE = .07, p < .001$, as did the recollection estimates $F(1, 13) = 11.36, MSE = .05, p < .001$. Paired $t$ tests indicated familiar targets and lures did not differ significantly in terms of familiarity ($t[13] = 3, p = .8$), although both estimates were elevated significantly relative to novel targets ($t[13] = 4.28, p < .005$ and $t[13] = 3.47, p < .005$, respectively). This pattern was repeated for the recollection estimates ($t[13] = 1.11, p = .3, t[13] = 3.9, p < .005$ and $t[13] = 3.1, p < .005$, respectively).

Overall, the model estimates can be interpreted as indicating the experimental manipulation involving pre-exposure of some study items increased source confusion, evidenced by the failure to discriminate familiar targets from familiar lures. Although the UVSD model estimates indicate this is because of equivalent elevated memory strength across the two conditions, the DPSD model attributes this result to both familiarity and recollection being increased in an equivalent manner for familiar targets and lures.

### Table 1. Proportion of Test Items Judged To Be from the Study List as a Function of Familiarization and Confidence Rating

<table>
<thead>
<tr>
<th>Familiarization</th>
<th>Pre-exposed</th>
<th>Novel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target</td>
<td>Certain</td>
<td>.49 (.05)</td>
</tr>
<tr>
<td>Lure</td>
<td>.43 (.06)</td>
<td>.22 (.03)</td>
</tr>
<tr>
<td>Type</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Certain</td>
<td>Probable</td>
</tr>
</tbody>
</table>

Data are means with SEM in parentheses.

### Imaging Data

Our first analysis examined old responses involving correct versus incorrect attribution of familiar items to the study list relative to misses. A repeated measures ANOVA revealed a significant main effect in bilateral hippocampus (left peak maxima: $-27, -27, -9; Z = 3.22$; right peak maxima: $39, -24, -18; Z = 3.39$). With these regions, a voxel-based $t$ contrast revealed increased activity for correct old responses relative to misses (left peak maxima: $-27, -24, -9; Z = 3.83, p < .001, k = 36$; right peak maxima: $30, -27, -9; Z = 3.47, p < .001, k = 8$). A second $t$ contrast of incorrect decisions versus misses revealed increased...
activity in identical regions of the hippocampus (left peak maxima: −27, −24, −9; Z = 3.74, p < .001, k = 32; right peak maxima: 30, −27, −9; Z = 3.35, p < .001; k = 8; Figure 3). No suprathreshold activity was observed in parahippocampal or perirhinal cortices in either hemisphere for these contrasts. A direct contrast of correct and incorrect old responses revealed no significant activity in the hippocampus, parahippocampal, or perirhinal cortices. Together, these results indicate that hippocampal activity is elevated for pre-exposed, familiar items and this activity does not differ according to the accuracy of list discrimination.

The abovementioned analyses examined decisions for familiar items that were rated both high (i.e., “sure old”) and low in confidence (i.e., “probably old”). However, recollection-based discrimination is considered to be reflected almost exclusively in high-confidence ratings (Yonelinas, 2002). We therefore examined activity associated only with the high-confidence old responses relative to misses. A repeated measures ANOVA revealed a significant main effect bilaterally in the hippocampus (left peak maxima: −30, −24, 12; Z = 3.35, p < .001; right peak maxima: 36, −24, −1; Z = 3.16, p < .001) and in the left posterior parahippocampal cortex (peak maxima: −9, −45, 0; Z = 3.96, p = .001). Planned voxelwise t contrasts in these regions revealed significantly increased activity bilaterally in the hippocampus (peak maxima: −33, −21, −12; Z = 3.96, p < .001, k = 35 and 30, −27, −9; Z = 3.16, p = .001, k = 13) and in the left posterior parahippocampal cortex (peak maxima: −9, −45, 0; Z = 3.96, p < .001, k = 9) for correct old responses. No suprathreshold activity was observed in the right parahippocampal cortex or in perirhinal cortex in either hemisphere. A second t contrast of high-confidence incorrect old responses versus misses revealed significantly increased activity in identical regions of left and right hippocampus (Z = 3.96, p < .001, k = 34; 3.12, p = .001, k = 12) and left posterior parahippocampal cortex (Z = 3.29; p = .001, k = 8; Figure 4). Again, no suprathreshold activity was observed in the right parahippocampal cortex or in perirhinal cortex in either hemisphere. Subsequently, a direct contrast of high-confidence old responses with correct versus incorrect list/source attributions failed to reveal any significant activity in the hippocampus, parahippocampal, or perirhinal cortices. In summary, the contrasts involving high-confidence old responses indicate that activity in the hippocampus and parahippocampal cortex is increased for familiar items and this activity does not differ according to the accuracy of list/source attribution.

Figure 2. Plots showing UVSD and DPSD model fits to the behavioral data. (A) UVSD sensitivity estimates (da) for targets and lures as a function of familiarization. (B) UVSD variance estimates (sa) as a function of familiarization. (C) DPSD recollection estimates for targets and lures as a function of familiarization. (D) DPSD familiarity estimates as a function of familiarization. Asterisk denotes a significant difference relative to novel studied items (p < .05).
Figure 3. Activity in the left and right hippocampus for “old” responses to familiar targets and lures relative to misses. Significant activation is shown at top superimposed on a coronal slice from the group average T1-weighted image in MNI atlas space, with accompanying beta values plotted below. Error bars represent SEM, and asterisks denote a significant difference relative to missed items (corrected $p < .05$).

Figure 4. Activity in left and right hippocampus and left posterior parahippocampal cortex for high confidence “old” responses to familiar targets and lures relative to misses. Significant activation is shown at top superimposed on coronal slices from the group average T1-weighted image in MNI atlas space, with accompanying beta values plotted below. Error bars represent SEM, and asterisks denote a significant difference relative to missed items (corrected $p < .05$).
DISCUSSION

In the present study, pre-exposed items were included in a list discrimination task to manipulate memory strength. At test, participants were asked to discriminate familiar and nonfamiliar targets from familiar and nonfamiliar lures. This resulted in a concordant pattern of increased “old” responses to familiar targets and lures, indicating participants had considerable difficulty discriminating familiar items included in the study list, consistent with prior behavioral research (McCabe & Geraci, 2009; Greene, 1999; Chalmers & Humphreys, 1998; Dobbins et al., 1998; Maddox & Estes, 1997). Model estimates indicated this was because of either equivalent increases in memory strength across the two types of items (UVSD model) or equivalent increases in both familiarity and recollection (DPSD model). Crucially, hippocampal activity was elevated in an equivalent manner for both familiar targets and lures. This was also the case when analyses were restricted to high-confidence responses, considered by the DPSD model to reflect the contribution of primarily recollection. Below, we discuss the extent to which these findings may be considered consistent with a memory strength account (e.g., Wais et al., 2010; Kirwan et al., 2008) or a DP account, including proposals of “false” or “noncriterial” recollection (e.g., Yonelinas & Jacoby, 1996). We also discuss the apparent differential effects of item repetition in item versus continuous recognition procedures (cf. Suzuki et al., 2011).

Familiarity, Veridical, and False Recollection

According to the DPSD model estimates, the concordant increases in old responses to familiar targets and lures were because of equivalent increases in familiarity and recollection across the two types of items. As recollection is usually characterized as veridical, involving retrieval of contextual details associated with a studied item (e.g., Yonelinas, 2002), the result for familiar lures seems counterintuitive. However, it might be interpretable in terms of “false” or “noncriterial recollection,” a possibility that was acknowledged by Wais et al. (2010) and Kirwan et al. (2008) in their fMRI studies, although not addressed explicitly with model estimates. Suzuki et al. (2011) also invoked noncriterial recollection (Yonelinas & Jacoby, 1996) to explain source memory results interpreted as supporting a memory strength account, although again no model estimates were provided.

Yonelinas and Jacoby (1996) introduced the concept of noncriterial recollection to explain results for difficult discriminations in the process dissociation procedure, demonstrating it was reflected solely in the inflation of DPSD model familiarity estimates. Inasmuch as the present task requires participants to use list membership as a basis for discriminative responding, and this was clearly difficult for the pre-exposed items, it nevertheless differs from process dissociation in that it does not involve separate inclusion and exclusion conditions. In addition, as noncriterial recollection is considered to be reflected in inflated familiarity estimates, it does not seem a valid explanation for the inflation of the recollection estimate for familiar lures and/or the concomitant increase in hippocampal activity if the hippocampus has a selective role in recollection as proposed by DP theorists (e.g., Eichenbaum et al., 2007; Brown & Aggleton, 2001). Moreover, given the concordant increases in DPSD model estimates of familiarity and recollection for both familiar targets and lures, it is unclear whether the accompanying increases in hippocampal activity are attributable to an increase in one of these processes or in some combination of the two. This is difficult to reconcile with proposals regarding selective roles for the hippocampus and perirhinal cortex in recollection and familiarity, respectively, particularly as we failed to observe significant perirhinal cortex activity (e.g., Eichenbaum et al., 2007; Brown & Aggleton, 2001).

Another possible interpretation of the data in terms of noncriterial recollection might involve acknowledging an apparent absence of learning in the present study, as participants demonstrated considerable difficulty discriminating items from familiarization and study lists. In this account, the participants’ responses might simply reflect recollection of an item’s appearance on the familiarization list, with (poor) discriminations between pre-exposed and study list items relying on this noncriterial recollection, although they were attempting to follow the task instructions. This would predict equivalent elevations in activity for the familiar targets and familiar lures assuming both true and noncriterial recollection were mediated by the hippocampus.5 However, even if we acknowledge that participants might have been inadvertently responding to familiarized items irrespective of their old or new status, this explanation implies there could not have been any “true” recollection, otherwise the participants would have been able to discriminate the familiar lures from items presented in the study list. Put succinctly, if DPSD model recollection estimates can reflect either true or noncriterial recollection, without quantifying the relative contributions of either type, the model loses its explanatory power. This is perhaps the reason why Yonelinas and Jacoby (1996) introduced their DPSD model explanation of noncriterial recollection solely in terms of inflated familiarity estimates.

Where participants have reported high-confidence old responses to lures, DP theorists have sometimes assumed that task instructions were not being followed properly (e.g., Yonelinas & Parks, 2007). If we instead assume that our participants failed to follow the task instructions for discriminating list context and were responding to words solely on the basis of their having been presented in the familiarization list, then it is possible both recollection estimates could be interpreted as reflecting “true” recollection of the familiarization list items. Hence, according to this explanation, the lack of differential hippocampal activity reflects “true” recollection for both familiar targets and
lures as the participants were treating them identically. Although we cannot exclude this possibility in the present study, a disadvantage of this explanation is that it is necessarily bespoke, and our preferred view is that the increase in old responses to familiar lures is a result of the experimental manipulation we employed, consistent with a number of prior studies (McCabe & Geraci, 2009; Greene, 1999; Chalmers & Humphreys, 1998; Dobbins et al., 1998; Maddox & Estes, 1997). For example, McCabe and Geraci (2009) also demonstrated recently that pre-exposing some items in a study list results in a significantly higher proportion of Remember judgments to familiar lures in the Remember–Know procedure. To accommodate this finding, DP theorists would likewise have to assume McCabe and Geraci’s (2009) participants failed to follow task instructions.

An alternative perspective is that the above results reflect source confusion or source misattribution, in which high-confidence responses to familiar lures represent recollection of details from an extralist context (e.g., McCabe & Geraci, 2009). According to the source-monitoring framework (e.g., Mitchell & Johnson, 2009), veridical and false recollection can arise from the same cognitive processes, hence similar brain mechanisms. Here, recollection is used as a descriptive label rather than denoting a distinct process. Therefore, its precise relation to DP model estimates is difficult to surmise. Source confusion or misattribution is also compatible with a memory strength account, as we elaborate below.

Memory Strength

The UVSD model sensitivity ($d_\prime$) estimates showed equivalent increases across familiar targets and lures relative to weak targets, a finding that may be interpreted as indicating memory strength was equivalent across the two types of item. This provides a relatively straightforward explanation of the poor discrimination observed. The equivalent hippocampal activity across familiar targets and lures, including that observed for only high-confidence items, may therefore be considered consistent with a memory strength account. This result corroborates findings using confidence ratings as a proxy for memory strength (Wais et al., 2010; also Kirwan et al., 2008) and, importantly, extends them to items strengthened via repetition at study.

Linear ROC curves such as the ones observed for the familiar targets and lures have often been interpreted solely in terms of the operation of recollection-based responding by DP theorists and have been considered inconsistent with the UVSD model prediction of a curvilinear ROC (e.g., Yonelinas & Parks, 2007; Quamme, Frederick, Kroll, Yonelinas, & Dobbins, 2002). However, it is worth noting that linear source memory ROCs tend to be the exception rather than the rule, with curvilinear ROCs being reported more frequently across studies (see Heathcote, Raymond, & Dunn, 2006). In fact, linear ROCs have been demonstrated to be a direct result of source confusion and are readily explained by the UVSD model (e.g., Slotnick & Dodson, 2005), consistent with the experimental manipulation employed here, or have been assumed to be a result of impoverished encoding (Heathcote et al., 2006).

A memory strength account might also be able to explain the absence of perirhinal cortex activity in the present study, as it proposes perirhinal cortex responses are elicited primarily for weak memories (Squire et al., 2007). Accordingly, the activity would be unlikely to be observable for items familiarized via multiple repetitions. However, several fMRI studies have observed increased perirhinal cortex activity for strong memories associated with either high-confidence ratings (Wais et al., 2010) or items repeated at study (de Zubicaray et al., 2011), inconsistent with this proposal.

Repetition in Item versus Continuous Recognition

The memory strength account of hippocampal activity has been challenged recently by the results of fMRI studies using the continuous recognition procedure (e.g., Suzuki et al., 2011; Johnson, Muftuler, & Rugg, 2008). According to these authors, if hippocampal activity reflects strong memories rather than recollection of contextual details associated with an item, then it should demonstrate a positive correlation with item repetition during continuous recognition. Item repetition is a longstanding method for manipulating recognition memory strength directly. To test this alternate view, Suzuki et al. (2011) examined judgments of temporal order for items presented up to four times, finding only reductions in hippocampal activity for successive presentations. They interpreted these results as being inconsistent with a positive correlation between retrieval-related hippocampal activity and memory strength (e.g., Squire et al., 2007). In the present study, familiar targets and lures were associated with increases in hippocampal activity. This result is consistent with the findings of our prior fMRI study involving repetition in item recognition memory (de Zubicaray et al., 2011). Consequently, it seems likely that different task demands might explain the different results reported for item and continuous recognition procedures.

The relative extent to which item and continuous recognition tasks index encoding and retrieval related processes is difficult to quantify, although in the former case an attempt is made to distinguish the two, at least operationally (Yassa & Stark, 2008). A number of authors have noted the likelihood of concurrent encoding of new and repeated items during continuous recognition (e.g., Johnson et al., 2008; Yassa & Stark, 2008; Brozinsky, Yonelinas, Kroll, & Ranganath, 2005). Johnson et al. (2008) interpreted the reductions in hippocampal activity observed with successive item presentation in their study as reflecting “new item encoding” that “likely played a minimal (if any) role in supporting recognition judgments.” To make judgments about
serial order in continuous recognition (e.g., Suzuki et al., 2011), participants need to encode temporal information, a requirement that is absent during typical retrieval tasks in item recognition memory.

However, repetition during associate learning has been shown to result in hippocampal activity increasing in a linear or graded fashion (Law et al., 2005). An alternate explanation may be that, unlike item recognition, continuous recognition engenders a long-term shift in response criteria according to the UVSD model, resulting in less evidence being required to support an “old” decision for later presentations (see Dunn, 2008). Consequently, a memory strength account would be consistent with a reduction in hippocampal activity with successive presentations in continuous recognition, if the activity is assumed to reflect the evidence needed to support a recognition decision (cf. Suzuki et al., 2011).

Summary and Conclusions
The proposal that hippocampal activity reflects memory strength rather than a distinct process of recollection within recognition memory has been challenged by recent interpretations invoking the operation of “false” or “nontarget recollection” and by findings of reduced activity for repeated items in continuous recognition procedures (e.g., Suzuki et al., 2011). Our results indicate that familiarization frequency is reflected in increased hippocampal activity in item recognition consistent with prior work (e.g., de Zubicaray et al., 2011) and, importantly, this occurs irrespective of the accuracy of list discrimination. Furthermore, increased hippocampal activity associated with high-confidence responses to pre-exposed lures is not due solely to an increase in familiarity as the DPSD model has assumed in terms of nontarget recollection (e.g., Yonelinas & Jacoby, 1996; cf. Suzuki et al., 2011). Reductions in hippocampal activity observed with successive presentations in continuous recognition may reflect a shift in decision criteria according to the UVSD model, resulting in less evidence being required to support an “old” decision. Overall, the present findings may be interpreted as supporting a positive correlation between hippocampal activity and memory strength, and highlight the need to consult UVSD and DPSD model estimates when interpreting results of fMRI studies of recognition memory.

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Notes
1. Following the behavioral literature, our analyses are confined to positive responses to items included in familiarization and study lists (e.g., Greene, 1999; Dobkins et al., 1998; Maddox & Estes, 1997). As Dobkins et al. (1998) note, comparisons of conditions that employ completely novel distractors to those in which the distractors have been seen in the experiment context one or more times are likely to introduce a confound, as the rejection of the two distractor types may rely on different cognitive processes.
2. The $d_+$ sensitivity measure from the UVSD model differs from the conventional $d'$ measure by permitting the variances of the old and new distributions to differ (Macmillan & Creelman, 2005). The values can be interpreted similarly.
3. We are indebted to an anonymous reviewer for suggesting this interpretation.

REFERENCES


