Neural correlates of memory confidence

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The present study aimed to shed light on the neural underpinnings of high vs. low memory confidence. To dissociate memory confidence from accuracy, the Deese–Roediger McDermott (DRM) paradigm was employed, which – compared to other memory paradigms – elicits a rather evenly distributed number of high-confident responses across all possible combinations of memory response types (i.e., hits, false alarms, correct rejections, and misses). In the standard DRM procedure, subjects are first presented with thematically interrelated word lists at encoding, which at recognition are intermixed with related and unrelated distractor items. The signature of a false memory or DRM effect is an increased number of high-confident false memories, particularly for strongly related lure items. For the present study, 17 female subjects were administered a verbal DRM task, whereas neural activation was indexed by fMRI. The behavioral analyses confirmed the expected false memory effect: subjects made more high-confident old responses (both hits and false alarms) the closer the items were related to the central list theme. Across all four memory response types, an increase in confidence at recognition was associated with bilateral activation in the anterior and posterior cingulate cortex along with medial temporal regions. In contrast, increments in doubt were solely related to activation in the superior posterior parietal cortex. To conclude, the study provides some evidence for dissociable systems for confidence and doubt.
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Introduction

Memory retrieval is by no means an all-or-nothing mechanism with a memory episode either being successfully recollected or not (Koriat et al., 2000). Rather, memory recollection is modulated by the degree of subjective confidence that an event or stimulus has been encountered previously. Thus, memory confidence serves as an important adaptive cognitive tool (Koriat and Goldsmith, 1996; Koriat et al., 2001): whereas conviction facilitates decisive actions, doubt cautions a subject to withhold a response and to prolong the

search process. Notwithstanding that memory confidence is not an optimal indicator for memory accuracy, numerous studies have confirmed that correct responses are usually accompanied by higher confidence ratings than are incorrect ones (see Keren, 1991; Moritz et al., 2003b, 2005). As a consequence, the impact of a correct selection is enhanced, whereas incorrect responses receive a "not trustworthy" tag thereby attenuating potential consequences of a wrong decision. If memory retrieval was just a binary all-or-nothing process (i.e., unmodulated by confidence), correct and incorrect responses would receive the same weight, which in the case of errors might have severe negative implications.

The investigation of memory confidence has been stimulated by research on eye-witness testimony and psychiatric disorders. For example, patients with obsessive–compulsive disorder (OCD) and schizophrenia (Koren et al., 2005; Moritz et al., 2005) display disruptions in the assessment of memory confidence. OCD patients appear to have a decreased memory confidence (Zitterl et al., 2001) despite rather uncompromised memory accuracy (Moritz et al., 2003a). Conversely, schizophrenia patients have been repeatedly found to be over-confident in memory errors while being at the same time under-confident in correct responses (Moritz et al., 2003b, 2005).

The neural pattern underlying memory confidence is yet poorly understood (Chua et al., 2006). Henson and coworkers (2000) detected activation in several prefrontal and parietal regions when subjects made low-confident vs. high-confident responses. No significant results were reported for the reverse analysis. In contrast, a recent study (Chua et al., 2006) on novel face recognition found no activation for low-confident vs. high-confident responses, whereas the opposite contrast was associated with activation of the anterior as well as posterior cingulate and medial temporal lobe. In general, regions associated with high confidence judgments mapped anatomically with limbic structures ("circuit of Papez"). Studies on *remember–know* judgments (i.e., vivid recollection vs. familiarity) are also relevant to this aspect of metamemory because *remember* judgments unlike *know* judgments are usually accompanied by high-confident responses (Moritz and Woodward, 2006; Yonelinas, 2001). Recollection, as measured by *remember* or source judgments, has been linked with activation in the posterior cingulate as well as medial temporal regions (Eldridge et al., 2000; Henson et

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al., 1999; Sommer et al., 2005; Yonelinas et al., 2005). More lateral areas, including the anterior and dorsolateral prefrontal cortex, have been recently linked to increases in familiarity confidence (Yonelinas et al., 2005). Feeling of knowing (FOK) represents another index of metamemory, which is defined as the feeling that one has some information in memory that is currently not retrievable but could be recollected either at a later time-point or when provided with cues. FOK has been linked to the prefrontal cortex (Kikyo et al., 2002; Schnyer et al., 2004, 2005), although there is some preliminary evidence for involvement of the parietal cortex as well (Maril et al., 2005).

Taken together, although the current literature strongly suggests an involvement of the posterior cingulate cortex as well as medial temporal areas in the modulation of memory confidence, a solid cortical signature of metamemory processes remains to be established. Importantly, studies differ whether or not the hippocampus and its adjacent cortices, whose involvement in episodic memory retrieval are undisputed (Squire, 1992), are also engaged in metamemory.

The present study explores memory confidence for different classes of memory responses (i.e., hits, false alarms, correct rejections, and misses). In particular, it was investigated whether memory confidence and doubt are represented in anatomically separable regions (see also Yonelinas et al., 2005): memory confidence could be modeled either as a single process (inhibition vs. excitation of the same cortical areas resulting in confidence vs. doubt) or independent processes. To meet the study purpose, the Deese–Roediger McDermott (DRM) paradigm (Deese, 1959; Roediger and McDermott, 1995) was administered. In the basic DRM procedure, lists of words (e.g., *hill*, *climb*, *valley*, *summit*, *top*, *molehill*, *peak*, *plain*, *glacier*, *goat*, *bike*, *climber*, *range*, *steep*) are consecutively presented to the participant, each converging on a so-called critical lure item (e.g., *mountain*). It has been shown (Deese, 1959; Roediger and McDermott, 1995) that healthy participants frequently falsely remember the semantically related lures to a large degree (50–80%) in a later recall or recognition trial. The DRM paradigm elicits a high number of high-confident as well as low-confident responses across the entire range of memory responses, whereas other memory paradigms typically produce only few false memories, thereby complicating the separation between accuracy with metamemory (confidence ratings).

Methods

Subjects

Seventeen right-handed healthy female participants took part in the investigation (mean age: 27.41 (SD: 7.51), range: 20–47 years). We selected a homogeneous sample with respect to gender and handedness because slight differences in brain activation for females vs. males may have added noise to the data (Cahill, 2006). Participants did not suffer from any neurological or psychiatric disorders as evidenced by a short interview. The entire session including practice trial, scanning period, and final assessment lasted approximately 2–3 h. Participants received a honorarium of 8€/h. Ethics approval was obtained from the local ethics committee.

Materials

The stimuli for the present study were derived in the course of a staged process. At first, a norming study was conducted, for which 55 healthy participants, none of whom took part in the later experiment, were requested to produce up to ten spontaneous associations for an entire set of 114 theme words. Subsequently, for each of the theme words, lists of 16 items (including the theme word) were compiled in descending order with respect to their response frequency. For example, the second word in the list (i.e., the item following the theme word) was the word most often produced in the association study. If list words shared the same association frequency, the final sequence was determined by the first author. Finally, eighteen lists were chosen which were later divided into three blocks comprising 6 lists each. The main selection criteria for word lists were minimal semantic overlap between lists (no shared associations) and suitability according to experts' opinion (e.g., good backward and forward associative strength).

To compile the items for the encoding and recognition phase, the word lists (excluding the first [theme] item) were divided into three groups of five words each (weakly related, medium related, and strongly related to the theme word). From each group one word was taken out to serve as a lure item in the recognition list. The remaining 12 words were shown during encoding. The theme word served as the so-called critical lure item. In the recognition phase all 16 items per list (12 studied, 4 non-studied items) were visually presented. Further, 12 recognition items were created per block, which were unrelated to any of the list words. Thus, the recognition list for each block (i.e., six lists) consisted of 72 old words (for each list 12 items were created: four strongly, four medium and four weakly related words of all six lists) and 36 new words (each one for every word list of the following types: critical lure, strongly related lure, medium related lure, weakly related lure as well as 12 unrelated new words).

fMRI experiment

For the fMRI experiment, an event-related design was employed which was administered in three blocks. Each block consisted of an encoding and a recognition phase, which were scanned in separate runs. During encoding, words from the six lists were visually presented each for 3 s, whereby lists were displayed in random order. As noted, each list contained 12 stimuli that were presented in descending semantic relatedness to the list theme. In order to ensure semantic processing of the stimuli, participants were asked to indicate whether each item was a noun or not via a key-press with their index or middle finger during encoding. Subjects were instructed that their recognition memory would be tested afterwards. The presentation of lists was separated by a pause of 10 s.

During the recognition phase, items were visually presented above a 6-point Likert scale: for each item, the subject was requested to move a red rectangle located at a random position to one of the six response alternatives (1=100% confident old, 2=rather confident old, 3=guessing old, 4=guessing new, 5=rather confident new, 6=100% confident new). In addition, we implemented a "response loop", so that subjects could switch between extreme response options (i.e., 1 and 6) with one button press only. This manipulation ensured that confidence ratings were not confounded with the number of button presses. Subjects were instructed that their responses only referred to the learning items that immediately preceded the recognition phase. For each recognition item, subjects were provided a response window of 4 s with the final position serving as response (i.e., no further

response confirmation was required). Subsequent to the recognition phase, the next encoding session was initiated. Stimuli presented at encoding and recognition differed in font and size to prevent physical matching (encoding, color: white, size: 40, font type: Times New Roman; recognition, color: white, size: 56; font type: Arial).

Image acquisition

Functional MRI was performed on a 3-T scanner (Siemens Trio) with a standard gradient-echo EPI T2*-sensitive sequence in 42 contiguous axial slices (2-mm thickness with 1 mm gap, TR 2.41 s, TE 25 ms, flip angle 70°, field of view 192 mm², 64×64 matrix resolution).

Image analysis

The images were slice-time corrected, realigned, normalized into standard anatomical space (MNI template; Friston et al., 1995), and smoothed with an isotropic Gaussian kernel of 10 mm full-width half-maximum using SPM2 (http://fil.ion.ucl.ac.uk/spm).

1st and 2nd level analysis

An event-related analysis of the imaging data was conducted using SPM2 to relate activity during recognition with confidence and accuracy judgments.

For the 1st level (subject-wise) analysis, the recognition trials were post hoc classified into four separate memory response types: hits (old response to studied items), false memories (old response to new items), misses (new response to studied items), and correct rejections (new response to new items). Each response category was further subdivided according to response confidence (100% confident, rather confident, guessing). Thus, the analysis involved 12 regressors for each individual: 4 memory response types (hits, false memories, misses, correct rejections)×3 confidence steps (high, medium and low confidence). The main contrasts of interest were high-confident vs. low-confident responses and vice versa. Serial correlations were modeled in the context of the AR(1) model. In order to remove baseline drifts and other low frequency components, the data were high-pass filtered with a cut-period of 120 s.

At the second level group analysis, all parameter estimates for each of the 12 regressors were subsequently included in a repeated-measures ANOVA treating subjects as random effects. The analysis was appropriately corrected for violations of the sphericity assumption of the general linear model (independent and identical errors).

Our statistical threshold was set at $p < 0.05$ corrected for multiple comparisons using the false discovery rate method (FDR; Genovese et al., 2002). In the absence of precise anatomical hypotheses, this correction procedure controls the percentage of false-positive activations in the entire brain volume. However, for displaying purposes all SPMs are shown at $p < 0.001$ uncorrected.

Results

Behavioral data

Participants correctly recognized 75% of the studied items (i.e., frequency of hits: 165; misses: 51; joint SD: 23). False

recognition occurred for 29% of the non-studied items (i.e., mean frequency of false memories: 34; correct rejections: 74; joint SD: 8).

A two-way 2×3 within-subject ANOVA was conducted with item type (old, new) and relatedness (strong [including critical lure items], medium, weak [including unrelated lure items]) as factors and mean responses per condition (ranging from 1 [100% old] to 6 [100% new]) as the dependent variable. The main effect of item type was significant, $F(1,16)=138.20$, $p < 0.001$, indicating that old items were more often classified as old than new items. In addition, the factor relatedness achieved significance, $F(2,32)=155.04$, $p < 0.001$: the closer an item was associated to the main list theme the higher correct and incorrect recollection. This was further qualified by a significant interaction, $F(2,32)=32.67$, $p < 0.001$: the effect of relatedness was stronger for new items than for old ones (see Fig. 1), presumably because the strong and the weak category for new items comprised extreme items (unrelated and critical lure items), which by definition do not exist for old items.

Neuroimaging data

Our statistical threshold was set at $p < 0.05$ corrected for multiple comparisons using the false discovery rate method (FDR; Genovese et al., 2002). In the absence of precise anatomical hypotheses, this correction procedure controls the percentage of false-positive activations in the entire brain volume.

High memory confidence (conviction) vs. low memory confidence (doubt) and vice versa

From Table 1 and Fig. 2, it can be derived that high-confident judgments were associated with large-scale bilateral activation in the anterior and posterior cingulate cortex, the (left) parahippocampal gyrus as well as in the right hippocampus across all memory response types (contrast: high-confident judgments>low-
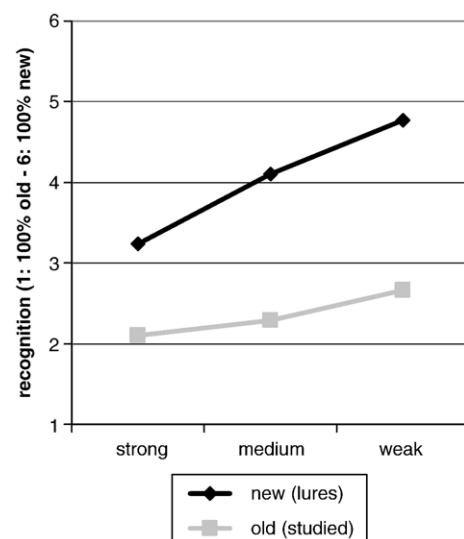

Fig. 1. Means for recognition ratings (1=100% old to 6=100% new). Irrespective of item type (old, new), items related to the central theme of the lists were more often judged as old relative to weakly related items. This linear effect was more pronounced for new items, as indicated by a significant interaction of item type and relatedness (see text).

Table 1
Activation pattern for high-confident responses vs. low-confident responses (MNI space)

	Left hemisphere			Z	Right hemisphere			Z
	x	y	z		x	y	z	
High-confident > low-confident								
Ant. Cingulate C.	−6	36	−6	5.63***	9	45	6	5.34***
Post. Cingulate C.	−3	−18	36	3.97**	0	−36	36	3.99**
Lingual G.	−15	−51	−9	5.08***				
Cuneus	3	−87	27	4.95***				
Parahippocampal G.	−27	−33	−12	4.16**	24	−24	−15	3.43*
Hippocampus					30	−15	−21	3.38*
Temp. pole					30	21	−21	4.01**
Putamen					30	−6	−6	3.89**
Med. Temp. G.					66	−27	−9	3.89**
Angular G.	−51	−66	39	3.76**				
Insula	−36	0	15	3.70**				
Cerebellum					27	−39	−30	3.53*
Low-confident > high-confident								
Post. sup. parietal					21	−69	51	4.05*

Notes. C. = Cortex; G. = gyrus; Med. = medial; Post. = posterior; Temp. = temporal. *** $p<0.001$, corrected (FDR), ** $p<0.005$, corrected (FDR), * $p<0.01$, corrected (FDR).

confident judgments). For all regions and all memory response types (i.e., hits, false memories, misses, correct rejections), the neuronal modulation of confidence followed a stepwise activation pattern (i.e., activation for high-confident responses, de-activation for low-confident responses). Contrasts also withstood correction according to the FDR method.

As can be seen in Fig. 3, the superior posterior parietal cortex showed significant activation for low confidence (doubt)

vs. high confidence ratings (conviction). This pattern of activation again was evident across all combinations of item and response types.

Correct vs. incorrect responses; hits vs. false memories

None of the contrasts for hits vs. false memories and vice versa achieved significance when correcting according to the FDR-method. However, for exploratory purposes we report regions at an uncorrected significance threshold of $p<0.001$.

At three regions (right lingual gyrus: $x=15$, $y=−60$, $z=−3$; $Z=3.88$; left calcarine: $x=−18$, $y=−69$, $z=15$; $Z=3.81$; right medial temporal cortex: $x=60$, $y=0$, $z=−18$; $Z=3.68$), correct responses (hits, correct rejections) yielded significantly more activation than incorrect ones (false memories, misses), whereas the opposite contrast revealed no significant activation.

When the analysis was confined to hits and false memories, high-confident hits yielded more activation than false memories in the left and right calcarine gyrus ($x=−18$, $y=−69$, $z=15$, $Z=3.63$; $x=12$, $y=−78$, $z=6$; $Z=3.32$), which are associated with visual processing, as well as in the left and right lingual gyrus ($x=−18$, $y=−57$, $z=−9$; $Z=3.50$; $x=18$, $y=−57$, $z=−6$; $Z=3.59$). As for the overall analysis, no significant activation appeared for the reverse contrast of high-confident false memories vs. hits.

When hits and false memory responses were collapsed irrespective of confidence strength, hits showed higher activation at the right occipitotemporal cortex ($x=42$, $y=−66$, $z=6$; $Z=4.02$), left putamen ($x=−27$, $y=−9$, $z=0$; $Z=3.92$), right temporal pole ($x=22$, $y=36$, $z=−12$; $Z=3.76$), and left calcarine ($x=−18$, $y=−66$, $z=18$; $Z=3.40$). The opposite contrast showed activation in the left inferior temporal lobe ($x=−39$, $y=−6$, $z=−27$; $Z=3.53$). This contrast maintained significance when the false memories were confined to critical and strong lures. False
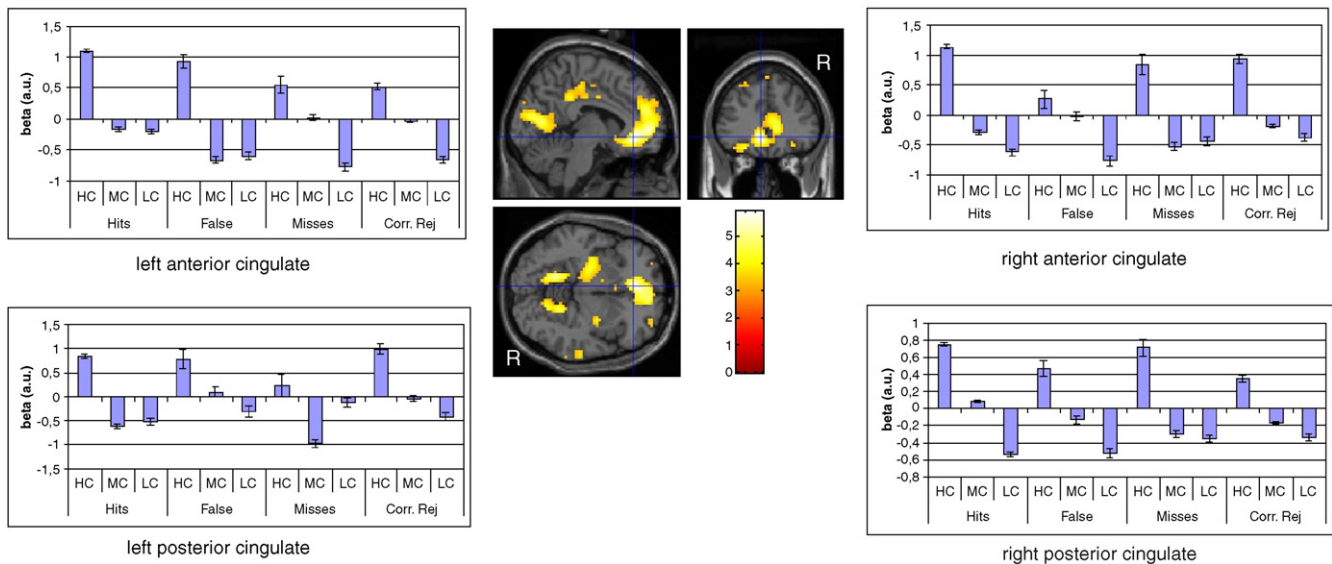

Fig. 2. Results from the contrast high-confident > low-confident projected on a T1 template brain (MNI space). Anterior as well as posterior cingulate regions were bilaterally activated for high vs. low-confident responses. Moreover, parahippocampal gyri on both sides and the right hippocampus showed activation as well. The left and right graphs display the parameter estimates (regression coefficients) at the peak voxel of each region for all 12 conditions (4 response types × 3 levels of confidence, error bars = SEM). The box graphs reveal that confidence-related activation in the anterior and posterior cingulate cortex followed a stepwise function for the four response types. *Notes.* HC = high confidence; MC = medium confidence; LC = low confidence.
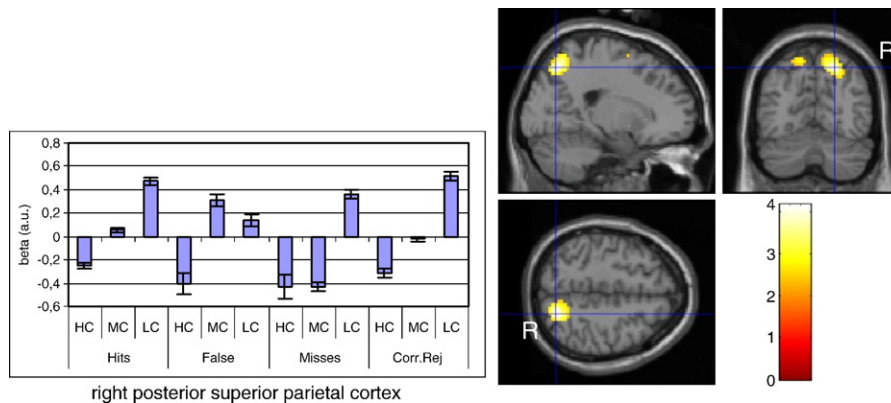
Fig. 3. Results from the contrast low-confident>high-confident projected on a T1 template brain (MNI space). The right posterior superior parietal cortex was more active for doubt-related relative to high-confidence responses, irrespective of memory response type. The left graph displays the parameter estimates (regression coefficients) at the peak voxel in this region for all 12 conditions (error bars=SEM). *Notes.* HC=high confidence; MC=medium confidence; LC=low confidence.

memories that were maximally medium related to the central theme were indistinguishable from hits with respect to brain activation.

Discussion

The present study employed the Deese–Roediger McDermott (DRM) paradigm to assess the neural substrate of memory confidence, irrespective of memory accuracy. On the behavioral level, the well-established false memory effect emerged (e.g., Roediger and McDermott, 1995): strongly interrelated word lists induced false recognition of lure items. In close resemblance to a recent study by Chua and coworkers (2006), memory confidence was associated with bilateral activation in the anterior cingulate cortex (ACC), posterior cingulate cortex, the parahippocampal gyrus, and the right hippocampus across all combinations of item and response type (i.e., hits, false memories, correct rejections, misses).

Interestingly, the reverse contrast (i.e., doubt>high confidence) yielded activation only in the right superior posterior parietal cortex. A recent study (Huettel et al., 2005) using a task that required subjects to base their decisions on a sequence of stimuli found activation in a similar region under induced uncertainty ($x=29$, $y=-70$, $z=48$). Thus, activation in the superior posterior parietal cortex may be a true reflection of doubt. Alternatively, attentional processes engaged to resolve conflict may be the core cognitive process behind this brain activation (Corbetta and Shulman, 2002). However, if this was the case, a concurrent activation rather than a de-activation of the ACC should be expected because this region plays a prominent role in conflict resolution.

Although the involvement of the medial temporal cortex and the posterior cingulate cortex come as no surprise given their established role in metamemory (Chua et al., 2006; Eldridge et al., 2000; Henson et al., 1999; Yonelinas et al., 2005), confidence-associated activation in the anterior cingulate cortex requires explanation as this region is usually tied to error monitoring and conflict detection (van Veen et al., 2004; Wang et al., 2005). Although speculative at this point, it deserves further investigation whether confidence-related activation in the ACC may be accommodated with its role in "guiding decisions about which actions are worth making" (Rushworth et al., 2004, p. 410), particularly reward expectancy (e.g., Matsumoto et al., 2003; Shidara and Richmond, 2002). This is because in many contexts high confidence will be equivalent to the promise of

reward: high-confident ratings express that subjects are certain about the outcome and validity of their decisions or actions (e.g., if I am sure about the correctness of my answer to a particular question in an exam, I expect high marks from the examiner). Also congruent with the mediating role of ACC in monitoring/appraisal and action selection, high-confident judgments enable a subject to perform determined and quick responses because the outcome of a context is (allegedly) foreseen.

The analysis revealed few differences between correct and incorrect recognition (hits vs. false memories and vice versa) in accordance with prior reports that differences between false and true items may not be accessible to conscious awareness (Schacter et al., 1997; Slotnick and Schacter, 2004). In a study conducted by Slotnick and Schacter (2004), which employed a non-verbal variant of the DRM false memory paradigm, early visual areas (Area 17, 18) successfully differentiated true from false memories consistent with the "sensory replay hypothesis" which posits that memory retrieval may re-engage early sensory cortices in order to aid subsequent successful retrieval. Because stimuli at encoding vs. recognition differed in physical aspects in the present study (font, size), studied items contained little perceptual recognition advantage over new items possibly explaining why no differences in these areas were observed. Another fMRI study using a verbal variant of the DRM paradigm (Cabeza et al., 2001) found stronger activation for true vs. lure items in the parahippocampal gyrus, whereas lure items elicited more activation than true items in the orbito-frontal cortex. However, this study is not comparable to our DRM study because recognition stimuli seemed to be differentiated according to item but not according to response types (i.e., false items in the Cabeza et al. study seem to comprise both misses and false alarms). Of note, we found greater activation in left temporal regions for false memories vs. hits. Against the background of few replicated stable fMRI correlates of false memories, we can at this point only speculate that this greater activation for strong or critical lure words is mediated by semantic networks hosted in this region (Saumier and Chertkow, 2002). Critical lure words in particular represent the gist of the entire word list and may thus elicit very strong spreading of activation in the inferior temporal lobe.

Whereas our results are in accordance with findings obtained by Chua et al. (2006), the current literature contains a number of inconsistencies presumably owing to procedural differences. Future studies should investigate several potential moderators for across-

study differences such as the ratio of new vs. old items and type of metacognitive rating. Notwithstanding certain similarities, feeling of knowing, remember-know, and confidence ratings tap different processes with possibly different patterns of activation. In addition, some studies including ours have combined accuracy with confidence ratings whereas other studies separated these concepts.

To conclude, the present study has demonstrated a consistent signature of memory confidence across different types of memory responses. The present results suggest the existence of a confidence-related mechanism hosted in the limbic system (particularly the anterior and posterior cingulate regions as well as the medial temporal lobe), and also provide preliminary evidence for the existence of a doubt-related mechanism hosted in the superior posterior parietal cortex.

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