

Research report

Dissociable neural correlates for familiarity and recollection during the encoding and retrieval of pictures

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Accepted 21 October 2003

Abstract

Results from behavioral studies have supported the idea that recognition memory can be supported by at least two different processes, recollection and familiarity. However, it remains unclear whether these two forms of memory reflect neurally distinct processes. Furthermore, it is unclear whether recollection and familiarity can be best conceived as differing primarily in terms of retrieval processing, or whether they additionally differ at encoding. To address these issues, we used event-related brain potentials (ERPs) to monitor neural correlates of familiarity and recollection at both encoding and retrieval. Participants studied pictures of objects in two types of study blocks and subsequently made remember–know and source memory judgments during retrieval. Results showed that, during encoding, neural correlates of subsequent familiarity and recollection onsetted in parallel, but exhibited differences in scalp topography and time course. Subsequent familiarity-based recognition was associated with a left-lateralized enhanced positivity and observed at anterior scalp sites from 300 to 450 ms, whereas subsequent recollection was associated with a topographically distinct right-lateralized positivity at anterior scalp sites from 300 to 450 ms and bilateral activity from 450 to 600 ms. During retrieval, neural correlates of familiarity emerged earlier than correlates of recollection. Familiarity was associated with an enhanced positivity at frontopolar scalp sites from 150 to 450 ms, whereas recollection was associated with positive ERP modulations over bilateral frontal (300–600 ms) and parietal (450–800 ms) sites. These results demonstrate that familiarity and recollection reflect the outcome of neurally distinct memory processes at both encoding and retrieval.

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Theme: Neural basis of behavior

Topic: Cognition

Keywords: ERP; Memory; Episodic; Recognition; Recollection; Familiarity; Encoding; Retrieval; Remember; Know; Source; Parietal; Medial Temporal; Prefrontal

1. Introduction

Findings from several studies have supported the idea that recognition memory may be supported by at least two processes: the assessment of an item's familiarity and the recollection of specific aspects of the episode during which an item was encountered [1,2,36,73]. Several behavioral methods have been used to successfully dissociate recollection and familiarity [21–23,28], but it is unclear whether these forms of memory reflect qualitatively and neurally distinct processes [34,59,74,75].

One hypothesis regarding familiarity and recollection is that they are largely overlapping, relying on the same neural system [34,39] but that recollection necessitates additional strategic processing at retrieval [31]. In support of this view, a recent meta-analysis of multiple empirical studies suggests that while various experimental manipulations can produce double dissociations between recollection and familiarity during retrieval, similar manipulations produce only single dissociations during encoding (see [73] for review). Collectively, these data would seem to suggest that recollection and familiarity rely on a similar neural system during encoding and may only be independent and dissociable at the time of retrieval, when controlled processing is essential for full recognition.

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An alternative hypothesis regarding familiarity and recollection is that they rely on functionally distinct neural systems (see [28,72] for reviews). Support for this view comes from studies of patients with medial temporal lobe lesions [2,75], suggesting that the hippocampus may be specifically critical for recollection, whereas surrounding regions in the rhinal cortex may be sufficient to support familiarity. Furthermore, some recent functional neuroimaging studies have shown that encoding related activity in the hippocampus and posterior parahippocampal cortex may support subsequent recollection whereas perirhinal activity may support subsequent familiarity [12,50]. If distinct neural systems support familiarity and recollection, as these studies suggest, then these processes should be dissociable both at the time of encoding and retrieval.

Further insight into the neural substrates of familiarity and recollection might be gained through the use of event-related brain potentials (ERPs) to monitor neural activity associated with these forms of memory. Most ERP studies of episodic memory that have attempted to dissociate neural correlates of familiarity and recollection have focused on measures of brain activity during episodic retrieval. Results from these studies suggest that different ERP “old–new” effects (i.e. ERP differences between studied and unstudied items) appear to differentiate between familiarity-based recognition and recollection, suggesting that the two forms of memory may rely on different neural processes at retrieval. For example, one old–new effect that has been termed the “FN400” appears as an enhanced negativity for new items compared to correctly recognized old items over frontal locations between 300 and 500 ms (see [19] for review). Some researchers have suggested that the FN400 old–new effect may be a neural correlate of familiarity-based recognition, because it dissociates recognized from correctly rejected (CR) unstudied items, but is insensitive to recollection [10,11]. Additionally, one recent study identified an early onset (100 ms) old–new effect, observed over frontopolar locations, that may also reflect familiarity [65]. However, to our knowledge, this latter effect has yet to be replicated or associated with familiarity-based recognition.

In contrast to early onset old–new effects, several late onset old–new effects have been proposed to be correlates of successful recollection (e.g. [19,48,49] for review). For example, many studies have identified a parietal maximal old–new effect occurring between 400 and 800 ms that has often been associated with recollection (see [30,52] for reviews). The “parietal old–new” effect is sensitive to factors believed to influence recollection, such as depth of processing [53,57], and is largest for items that elicited correct source [49,63,70,71] or “remember” judgments [14,60,64]. However, it remains unclear whether the parietal old–new effect is purely reflective of recollection or a unitary

retrieval process that varies in a graded fashion [14,60,63,64,70,71].

Several ERP studies have shown that, in addition to retrieval, patterns of brain activity during encoding can differentiate items that will be subsequently correctly recognized from items that will subsequently be forgotten (e.g. [58] see also [30,52] for reviews). This activity typically takes the form of an enhanced positivity for subsequently recognized compared to subsequently forgotten items. These ERP effects have been termed “differential neural activity due to memory” or “Dm” effects [45] and have been posited to reflect neural correlates of successful memory formation [16,45].

If recollection and familiarity are supported by different types of representations, one would expect these types of memory to be associated with different patterns of Dm effects. Unfortunately, few studies have attempted to dissociate Dm effects at the time of encoding [20,37,60]. Although each of these studies [20,37,60] used the “remember–know” procedure [66] to differentiate items that were subsequently recollected from items that were subsequently recognized on the basis of familiarity, results from these studies were inconsistent. One study reported topographically widespread Dm effects for all subsequently recognized items between 200 and 900 ms but no differences were observed as a function of recollection or familiarity [60]. Another study found Dm effects for recollected (i.e. items that subsequently elicited a “remember” response), but not for familiar items (i.e. items that subsequently elicited a “know” response) between 400 and 1100 ms, maximal over left frontal sites [20]. A third study found what appeared to be distinct neural correlates of both recollection and familiarity Dm effects [37]. They showed that while a left temporal maximal negativity at 400 ms was correlated with subsequent familiarity, sustained bilateral frontal positivity between 1000 and 2000 ms predicted recollection. However, they did not report topographical analyses to indicate whether these effects were qualitatively distinct [40,51]. Thus, it remains unclear whether distinct neural processes may support recollection and familiarity at the time of encoding.

In addition to determining whether recollection and familiarity would be associated with distinct patterns of activity, another objective of the present study was to characterize the nature of visual memory representation. Several behavioral studies of recognition memory have demonstrated that visual stimuli are better remembered if presented to the same rather than opposite visual hemifield at study and test (e.g. [3,24]). In addition, one ERP study found that when abstract visual line patterns were presented laterally at encoding and centrally at retrieval, a greater physiological response, as measured by ERPs, was elicited over the hemisphere contralateral to initial stimulus presentation during encoding [24]. Together, these data suggest that visual memories may be organized in a

contralateral fashion. If so, then it follows that recollection and familiarity effects for laterally presented stimuli might also be associated with contralaterally enhanced memory traces.

The present study, schematically depicted in Fig. 1, was designed to address the aforementioned issues. ERPs were recorded while participants studied, and subsequently retrieved from memory, photographs of concrete objects. In alternating blocks of study trials, subjects either performed animacy (“Is this living or nonliving?”) or manipulability (“Is this a manipulable object?”) judgments on laterally presented objects. During test blocks, a series of studied and unstudied foil objects were centrally presented and subjects made “remember–know–new” judgments on these objects. For items eliciting remember or know responses, subjects additionally made source decisions about which study block (animacy or manipulability) the object was encountered in. This allowed us to verify that remember and know responses were associated with recollection (contextual) and familiarity (a contextual) processes, respectively (see [72] for review). ERPs were then sorted by test responses for both encoding and retrieval phases.

We hypothesized that if recollection and familiarity-based recognition are supported by different types of neural representations [1,2,15], we would expect that they would be associated with qualitatively distinct patterns of neural activity at encoding and retrieval. In addition, we hypothesized that if visual memories are contralaterally organized for laterally presented objects, then contralateral enhancements of memory effects should be seen at encoding and retrieval.

2. Methods

2.1. Subjects

Thirteen young adults (nine females, mean age 19 years, age range 18–25) recruited from local universities participated in the experiment. Subjects were paid for participation and signed consent statements approved by the Institutional Review Board of the University of California, Berkeley. Subjects were right-handed and all had normal or corrected to normal vision. None of the participants had a history of psychiatric or neurological disorder or psychoactive drug use. Data from four additional subjects were discarded due to excessive non-correctable eye artifacts.

2.2. Stimuli

Stimuli were presented on a PC controlled monitor against a white background. Stimuli consisted of 500 grayscale photographs of meaningful objects. Each stimulus subtended a visual angle of $7.87^\circ \times 10.98^\circ$.

2.3. Procedure

All participants were seated comfortably in a dimly lit and sound-attenuated booth facing a computer screen at a distance of 1 m. Subjects were instructed to fixate centrally throughout stimulus presentation and to minimize all unnecessary movements. Subjects responded to stimuli by button press on a joystick held in the right hand and in all cases, accuracy was emphasized over speed. Participants were trained on each task and instructions were repeated

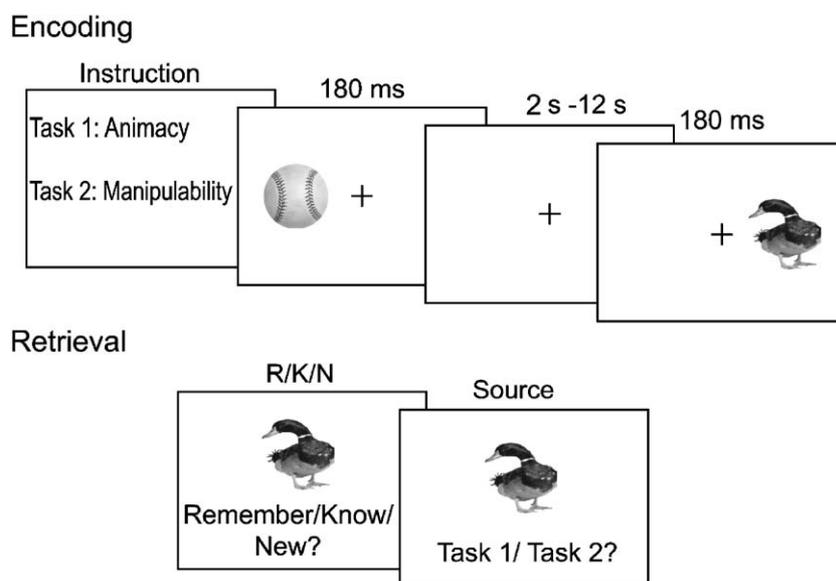


Fig. 1. Schematic of the experimental design showing sample stimuli and task requirements.

verbally throughout the duration of the experiment. Subjects were informed that they would be tested on their memory for all studied objects.

EEG and behavioral responses were collected during six blocks of study trials and three blocks of test trials. Blocks were ordered study–study–test, such that each block of test trials covered the items that were studied in the two preceding study blocks. On each block of study trials, 50 stimuli were presented one at a time 4.15° either to the left or right of a central fixation cross for a duration of 180 ms and a randomized stimulus onset asynchrony (SOA) of between 2 and 12 s, (mean 4 s)¹. Half of the stimuli were randomly presented to the left and half to the right of fixation in a random sequence. In three of the study blocks, subjects were asked to determine the animacy of each object by pressing 1 for living and 2 for non-living. In the other three study blocks, subjects were asked to determine the manipulability of each object by pressing 1 if manipulable and 2 if non-manipulable. Subjects completed one of each type of study block and were allowed a few minutes to relax before proceeding to the corresponding test block.

Each block of test trials included 100 objects that were studied in the preceding two test blocks and 50 new objects in a pseudorandom sequence. Instructions for the test phase included a description of the appropriate use of the “remember”, “know” and “new” response categories, modeled after previous studies [23,47]. Subjects were instructed to respond “remember” if they were certain they had seen the object and could recollect specific associations that occurred at study, “know” if they were less certain about previously studying the object and could not recollect any specific associations and “new” if they were certain they had never previously studied the object. Objects were all centrally presented above a response cue (“Press 1”=remember (R), “Press 2”=know (K), “Press 3”=new (N)), both of which remained on the screen until a response was made. If subjects responded “new”, a centrally presented fixation cross appeared for 500 ms until the next test stimulus was presented. If a “remember” or “know” response was made, a new response cue appeared in place of the previous asking the subjects to judge whether the object was studied in the animacy or manipulability task (“Press 1”=animacy, “Press 2”=manipulability). Once subjects made this second response, a centrally presented fixation cross appeared for 500 ms until the next test stimulus was presented. All reaction times (RTs) faster than 200 ms or slower than 4 s were considered trial failures and not analyzed. On average, this resulted in the rejection of less than 19% of trials. All 13 subjects’ data were available for behavioral analyses.

¹ We conducted preliminary statistical tests to determine whether SOA interacted with subsequent memory performance. ANOVA gave no rise to the factor of SOA and thus, we collapsed across SOA for all subsequent analyses.

2.4. ERP recording

EEG data was collected for both study and test phases of the experiment. The EEG was recorded from 63 Ag/AgCl electrodes in an elastic cap. Only electrodes in which impedances were reduced below 10 k Ω were examined. All of the electrodes were referenced to a pair of linked electrodes placed on the mastoid processes. The vertical electrooculogram (EOG) was recorded from an electrode placed below the right eye and the horizontal EOG from electrodes placed on the outer canthi of both eyes. All channels were amplified at 20 K and online bandpass filtered from 0.1 to 80 Hz. The data were sampled at a rate of 256 Hz and stored for offline analysis. Recording epochs containing amplifier saturating artifacts ($\pm 100 \mu\text{V}$) that occurred between 100 ms pre-stimulus to 800 ms post-stimulus were excluded prior to averaging. Epochs with correctable eye movements were corrected by a method based on principal component analysis, as is available in Neuroscan version 4.1 [4]. Extensive analysis of this method determined that there was no reduction in waveform resolution.

2.5. ERP analysis

For any effect to be included in analysis, we required that there be at least 10 participants with at least 15 artifact-free trials of that trial type. This resulted in 10 subjects’ available data for encoding ERP analyses, with one additional subject’s data available for retrieval ERP analyses. ERPs were analyzed from 10 electrode sites (FP1, FP2, AF3, AF4, F3, F4, C3, C4, P3, P4), where condition effects were most evident and where previous studies which have used similar experimental design have reported such effects [20,65]. In order to examine whether stimulus presentation during study sufficiently lateralized visual processing and, therefore, early extrastriate ERPs, we measured P1 and N1 mean amplitudes and peak latencies over select extrastriate sites (PO3, PO4) between 90 and 120 ms for the P1 and 125–225 ms for the N1 (see [38] for review). No behavioral or ERP differences in memory-related effects were observed as a function of study task (animacy/manipulability) at encoding or retrieval, as related to memory. Thus, all data were collapsed across study task for memory-related analyses.

Specifically, ERPs to objects presented at study and test were averaged separately, first as a function of visual field of presentation during study (left vs. right) and then based on the subject’s behavioral response at test. Thus, ERPs to objects at encoding and retrieval were averaged separately for recognized items that elicited “remember” (R) or “know” (K) responses and for missed items that were misidentified as “new” (M). ERPs were also averaged for CR new objects during retrieval. Given the high levels of accuracy in this study, false alarm rates were too low to adequately estimate responses to new items that elicited R or K judgments. ERPs sorted as a function of source memory accuracy were roughly

similar to those sorted by R and K judgments, only statistically less robust, as observed in prior studies (e.g. [20,56]). This pattern of results could reflect the fact that ERP correlates of recollection derived from the source memory task were contaminated by correct guesses when items were not actually recollected. Furthermore, ERP correlates of familiarity derived from the source memory task may have been contaminated by items that were recollected, despite the fact that information relevant to the source judgment was not recovered. For these reasons, we do not additionally report on the source memory ERPs here and both R and K trials were collapsed across source hits and misses.

Based on these considerations, our analyses of study and test phase ERPs concerned the identification of potentials related to recollection and familiarity. To quantify these effects, statistical analyses were performed on mean ERP amplitudes for the various conditions over successive 150 ms time windows, with the exception of the last time window, in which amplitudes were analyzed over the last 200 ms of the epoch. In order to restrict the number of comparisons, an omnibus ANOVA based on all electrodes was first performed to determine if any significant effects existed for the different trial types. In the event of a significant main effect or interaction, planned comparisons were performed for each electrode pair to further characterize the topography and significance of the effects within each latency range. Reported *P*-values reflect the Huynh–Feldt correction where appropriate. Significant main effects and interactions at an alpha (α) level of 0.05 were followed up with *t*-tests to determine the source of the effects. Additionally, for test phase ERPs, missed items (M) were contrasted with correctly rejected new items (CR) with the

statistical procedure described above. In the event that no reliable differences were found in any time window, (M) items would be contrasted with (R) and (K) items at test, for consistency with study phase comparisons.

The planned comparisons described above were intended to address our goal in characterizing the differences in brain potentials related to recollection and familiarity. Based on prior characterizations of the remember–know method [33,74], we reasoned that K judgments are based solely on familiarity and that the difference in potentials elicited by K versus M items could be interpreted as a neural correlate of familiarity-based recognition. In contrast, we reasoned that because R and K judgments primarily vary in terms of recollection, a difference in brain potentials elicited by R versus K items could be interpreted as a neural correlate of recollection. Accordingly, main effects or interactions in the ANOVAs described above were followed up with planned contrasts to determine if the effects were related primarily to familiarity, recollection, or both. It should be noted that reliable main effects or interactions could also be due to R versus M, which we do not include in our characterizations of recollection and familiarity in the follow up tests. Finally, we note that a critical question in neuropsychological and neurophysiological characterizations of recollection and familiarity is whether these processes are actually mediated by distinct neural systems [1,2,39,75]. To this end, topographic maps of surface potentials, calculated by spherical spline interpolation [46], were used to display the scalp distributions of recollection and familiarity effects. ANOVAs contrasting these topographies were performed after the corresponding difference waves had been rescaled by the vector length method [40,51].

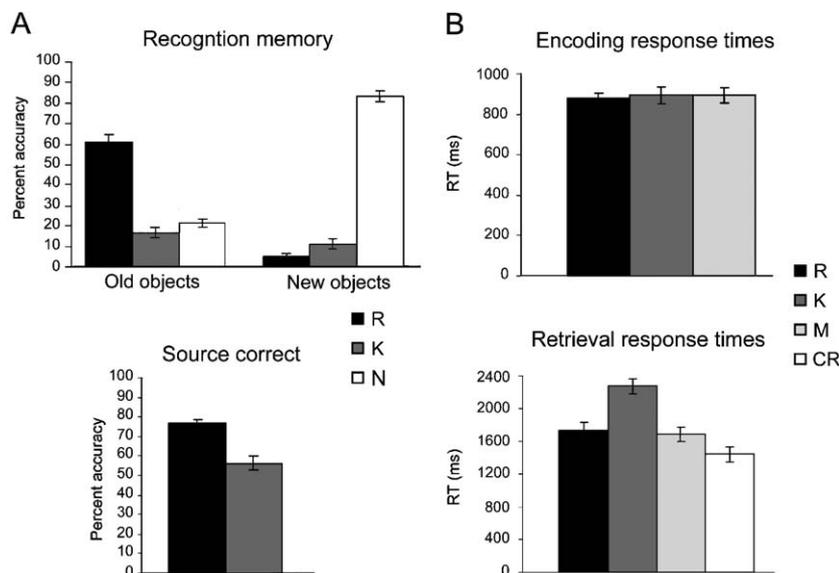


Fig. 2. (A) Proportions of “remember” (R), “know” (K) and “new” (N) responses given to old and new items at test and proportion of correct source judgments for studied items that elicited R and K responses (left). S.E.M. bars are shown. (B) Study phase RTs for items subsequently associated with “remember” (R), “know” (K) and “new” (i.e. Miss/(M)) judgments and test phase RTs for R, K and M old items and CR new items (right). S.E.M. bars are shown.

3. Results

3.1. Behavioral results

No differences in behavioral performance were observed as a function of visual field of presentation (left vs. right), either during study or test. Thus, all behavioral data were collapsed across visual field for subsequent analyses.

Subjects were highly accurate in both the animacy, 89% (S.D.=2), and manipulability, 77% (S.D.=4), tasks at encoding. Statistical analyses showed that subjects were more accurate in the animacy than in the manipulability task at encoding [$t(12)=7.67, P<0.0005$]. Likewise, RTs were significantly slower during the manipulability, 954 ms (S.D.=126), than animacy task, 829 ms (S.D.=114), [$t(12)=7.91, P<0.0005$].

Although accuracy and RTs differed between the animacy and manipulability tasks at study, behavioral results indicated that the two tasks elicited equivalent levels of subsequent memory performance. Similar proportions of items from both tasks were subsequently recognized at test, as measured by RKM and source judgments, [$F(2,24)$'s $<2.7, P$'s >0.1]. Thus, as noted previously, all subsequent analyses of behavioral and ERP data were collapsed across study task.

Analyses of test-phase data revealed that subjects exhibited high levels of memory performance. The mean proportions of R, K, and N judgments for old and new items presented at test are shown in Fig. 2(A). Hit rates for R and K judgments were both significantly greater than their respective false alarm rates when scored on raw mean values [$t(12)$'s $>2.62, P$'s <0.02]. The difference between K hit and false alarm rate was even more robust when scored under an independence assumption [74], where $hit = 0.17 / (1 - 0.61) = 0.44$ and $false\ alarm = 0.11 / (1 - 0.05) = 0.12$, [$t(12) > 6.56, P < 0.0002$]. As shown in Fig. 2(A), source memory accuracy was significantly higher for R than K judgments [$t(12) = 5.49, P < 0.0005$], providing objective

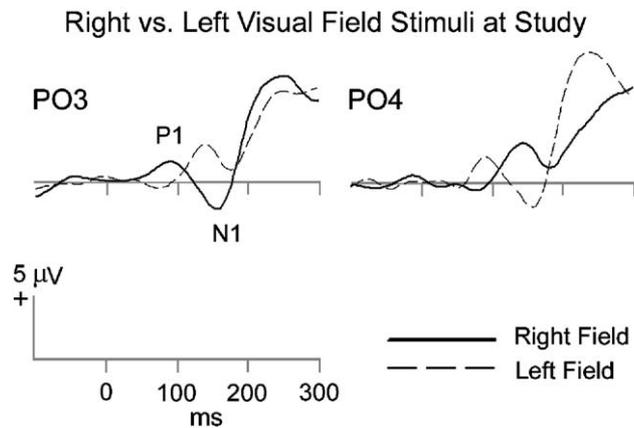


Fig. 3. Visual field effects on grand mean P1/N1 extrastriate potentials at study.

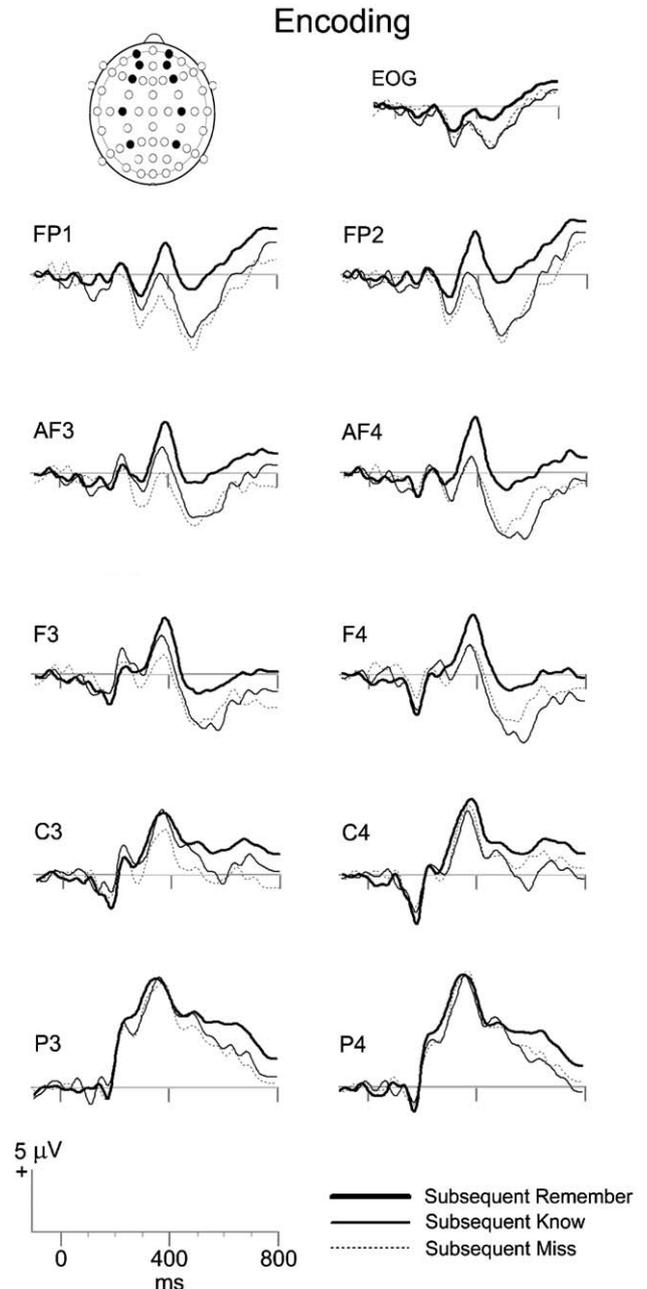


Fig. 4. Grand mean ERPs during encoding for objects subsequently recognized and given “remember” or “know” judgments, or unrecognized and given “new” (i.e. miss) judgments. Left and right columns correspond to left and right scalp locations, respectively. Shaded circles show scalp locations for displayed electrodes.

evidence to support the idea that R items elicited higher levels of recollection than did K items.

Mean RTs for encoding task judgments are shown as a function of subsequent memory performance in Fig. 2(B). An ANOVA revealed no significant differences in study phase RTs between studied items that elicited R, K, or M judgments [$F(2,24) < 1$]. Mean RTs for each judgment type during the test phase are also shown in Fig. 2(B). An ANOVA of these RTs did reveal significant differences

between the three trial types [$F(3,36)=33.28$, $P<0.0005$], and follow-up tests showed that RTs were longer for K judgments than R, M or CR judgments [all $t(12)$'s >2.7 , P 's <0.018]. Mean RTs did not differ for R and M judgments [$t(12)<1$].

3.2. ERP results

3.2.1. Laterality effects

P1 and N1 potentials elicited by study items presented in the left and right visual fields are depicted in Fig. 3. ANOVAs for mean amplitude and peak latency revealed significant interactions between hemisphere (left vs. right) and visual field (left vs. right) at extrastriate locations (PO3, PO4) in each case for both latency and amplitude, [all $F(1,9)$'s >20.0 , P 's <0.001]. As can be seen in the figure, both P1 and N1 potentials were enhanced and had shorter latencies to contralaterally presented stimuli.

Despite reliable lateralization of visual processing during study, as evidenced by the above analyses, ERPs sorted first as a function of visual field of presentation during study and then by behavioral performance (R, K, M) were roughly similar for left and right field stimuli (data not shown). In addition, preliminary omnibus ANOVAs gave no rise to an interaction between the factor of visual field (left vs. right) and condition (R, K and M) during any time window, either during study or test. Thus, all data were collapsed across visual field for subsequent analyses.

3.2.2. Study ERPs to subsequently remembered, known and missed items

ERPs elicited by study items subsequently given “remember,” “know” and “new” (i.e. miss) judgments are shown in Fig. 4. As shown in the figure, ERP activity during

encoding differed as a function of subsequent memory Dm [43,45] performance.

Mean ERP amplitudes to study items were computed at left and right electrodes for frontopolar, anterior–frontal, frontal, central and parietal locations (as depicted in Fig. 4) and analyzed over successive 150 ms time windows from 150 to 600 ms and in the time window from 600 to 800 ms. Preliminary omnibus ANOVAs for each separate time window revealed a significant interaction between condition (subsequently R, K and M) and hemisphere (left vs. right) in each case [all $F(2,18)$'s >4.42 , P 's <0.03]. Thus, we performed more focused comparisons for each time window to further characterize these effects. The results of the condition \times hemisphere ANOVAs for each electrode pair are shown in Table 1.

For the 150–300 ms interval, significant condition \times hemisphere interactions were found at frontal and central locations. However, follow-up contrasts did not reveal significant subsequent recollection or familiarity effects at these locations.

For the 300–450 ms interval, main effects of condition were found at the frontopolar and anterior–frontal sites. In addition, condition \times hemisphere interactions were found at anterior–frontal, frontal and central locations. As can be seen in Fig. 4, these interactions reflected the strongly left-lateralized familiarity (K–M) and greater right-lateralized recollection (R–K) effect at these locations. Follow-up contrasts revealed that significant familiarity effects were evident at left anterior–frontal, frontal and central locations [all $t(9)$'s >2.40 , P 's <0.04] but not at homologous right hemisphere sites or at either frontopolar location. In contrast, subsequent recollection effects were observed at the right frontopolar, anterior–frontal and frontal sites [all $t(9)$'s >2 , P 's <0.05] but not at the homologous left hemisphere sites or at either central location.

Table 1

ANOVA results for encoding phase ERPs as a function of subsequent memory for main effect of condition and condition by hemisphere interactions

Location	Effect	Latency window (ms)							
		150–300		300–450		450–600		600–800	
		$F(2,18)$	P	$F(2,18)$	P	$F(2,18)$	P	$F(2,18)$	P
Frontopolar (FP1/FP2)	Condition	–	–	5.64	0.024	3.61	0.04	–	–
	Interaction	–	–	–	–	–	–	–	–
Anterior–frontal (AF3/AF4)	Condition	–	–	6.25	0.016	6.0	0.017	–	–
	Interaction	–	–	4.46	0.033	–	–	–	–
Frontal (F3/F4)	Condition	–	–	–	–	4.04	0.039	–	–
	Interaction	5.19	0.017	4.34	0.037	–	–	–	–
Central (C3/C4)	Condition	–	–	–	–	4.14	0.033	3.94	0.038
	Interaction	4.22	0.047	5.88	0.011	2.76	0.09	4.96	0.02
Parietal (P3/P4)	Condition	–	–	–	–	–	–	2.88	0.082
	Interaction	–	–	3.08	0.071	–	–	5.09	0.018

Note: Significant effects ($\alpha=0.05$) are shown in bold. Dashes represent F -values <1 and P -values >0.1 . †, Signifies that follow-up contrasts revealed significant subsequent familiarity effects. ‡, Signifies that follow-up contrasts revealed significant subsequent recollection effects.

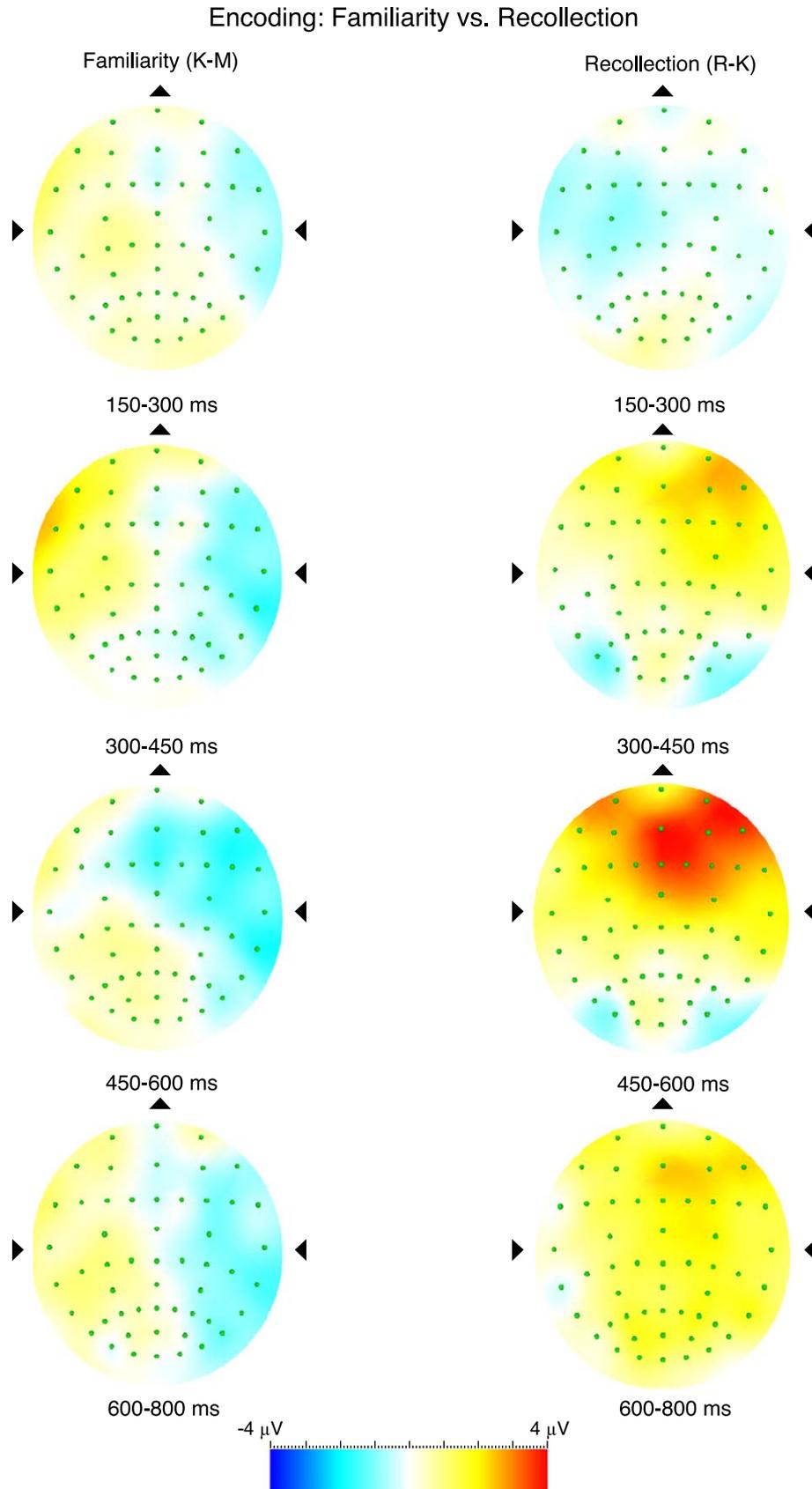


Fig. 5. Topographic maps depicting the time course of subsequent familiarity (K–M) and subsequent recollection (R–K) effects at study. Small circles represent electrode locations as viewed from above.

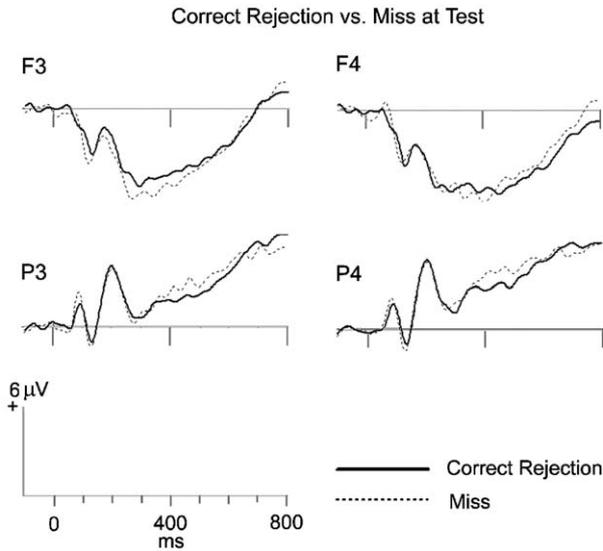


Fig. 6. Grand mean ERPs for correct rejections vs. miss trials at test.

For the 450–600 ms interval, main effects of condition were seen at frontopolar, anterior–frontal, frontal and central locations. Follow-up contrasts revealed no significant familiarity effects at any of these locations, but significant recollection effects were observed bilaterally at frontopolar, anterior–frontal and frontal sites [all $t(9)$'s > 2.26, P 's < 0.04] but not at the central sites.

Finally, during the 600–800 ms interval, there was a main effect of condition at central locations and condition \times hemisphere interactions at central and parietal locations. However, follow-up contrasts did not reveal significant familiarity (K–M) or recollection (R–K) effects at these locations.

In summary, the above analyses confirmed that ERPs recorded during encoding predicted both familiarity and recollection. A left-lateralized subsequent familiarity effect, maximal at anterior scalp sites, was observed in the 300–450 ms window. In addition, a right-lateralized subsequent recollection effect, maximal at anterior scalp sites, was observed from 300 to 450 ms and was sustained bilaterally through 600 ms.

3.2.3. Topographical comparisons of subsequent familiarity and recollection effects

In addition to characterizing the magnitude and time course of subsequent memory effects, two types of topographical analyses were performed on encoding phase ERPs. The first compared the subsequent familiarity and subsequent recollection effects in the 300–450 ms epoch in which both effects were significant. The purpose of this analysis was to determine whether the familiarity and recollection effects reflected the engagement of distinct configurations of neural generators [52].

The scalp distributions for the subsequent familiarity (K–M) and recollection (R–K) effects are shown in Fig. 5. As described earlier, each of these difference waves was

rescaled by the vector-length method across all electrodes [40] and entered into a memory effect (subsequent familiarity vs. subsequent recollection) \times location (frontopolar, anterior–frontal, frontal, central and parietal) \times hemisphere (left vs. right) ANOVA for the 300–450 ms latency window. This revealed a significant memory effect \times hemi-

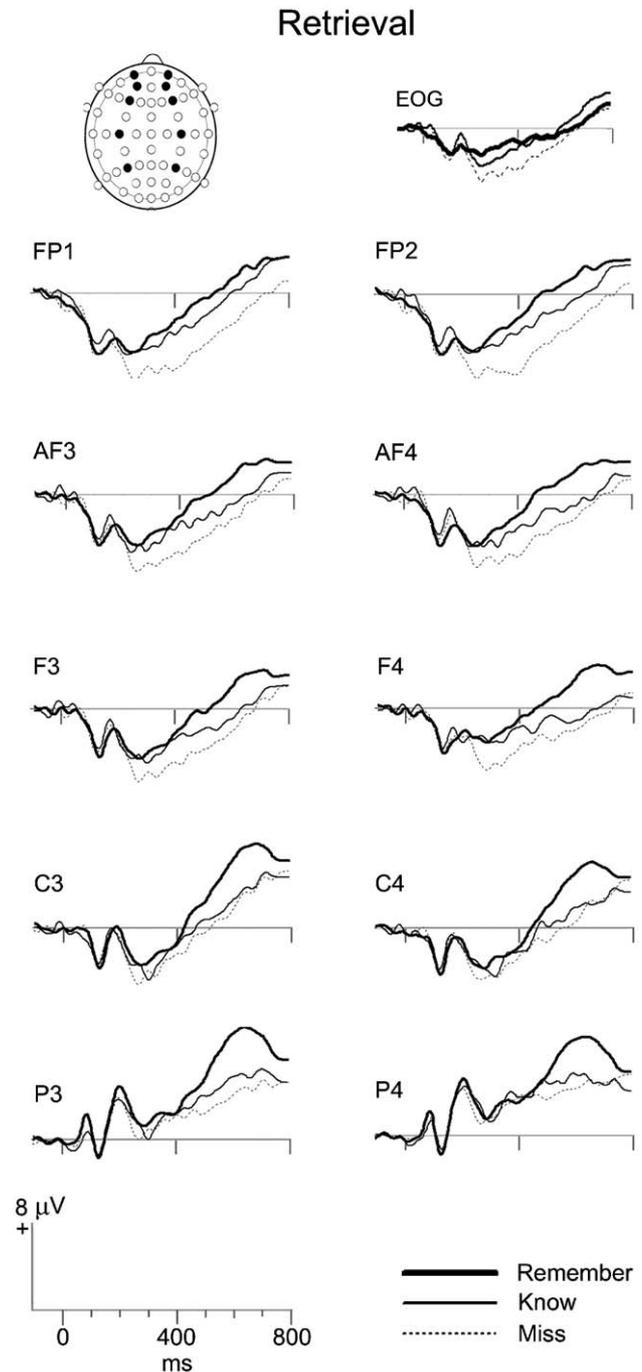


Fig. 7. Grand mean ERPs during retrieval for objects recognized and given “remember” or “know” judgments, or unrecognized and given “new” (i.e. miss) judgments. Left and right columns correspond to left and right scalp locations, respectively. Shaded circles show scalp locations for displayed electrodes.

hemisphere interaction [$F(1,9)=11.84, P=0.007$] as well as a marginal three-way interaction between these factors and location [$F(4,36)=3.04, P=0.06$], indicating the largely anterior distribution of these effects. These findings confirmed that the subsequent familiarity and recollection effects, though overlapping in time, reflected qualitatively different patterns of encoding activity.

A second analysis was performed to determine whether the topography of the subsequent recollection effect changed over time. To address this question, rescaled recollection effects during the 300–450 and 450–600 ms latency windows were submitted to a latency (300–450 vs. 450–600 ms) \times location (frontopolar, anterior–frontal, frontal, central and parietal) \times hemisphere (left vs. right) ANOVA. This revealed only a marginal latency \times location \times hemisphere interaction [$F(3,36)=2.221, P=0.08$]. As can be seen in Figs. 4 and 5, this effect appeared to be bilaterally distributed over anterior locations but still stronger on the right side in the later time window, contributing to the marginal significance of this interaction.

3.2.4. Test ERPs to remembered, known and missed studied items

Consistent with previous observations [65,70], ERPs to missed old (M) items did not qualitatively differ from CR new item ERPs, as can be seen in Fig. 6. In light of the fact that omnibus ANOVAs did not reveal any significant effects of condition (CR vs. M) in any time window, we restricted our analyses of retrieval phase ERPs to comparisons between R, K and M items.

ERPs to study items associated with “remember,” “know” and “new” (i.e. miss) judgments are shown in Fig. 7. Preliminary omnibus ANOVAs for each separate time window revealed a significant interaction between

condition (R, K and M) and location (frontopolar, anterior–frontal, frontal, central and parietal) for the first two windows [$F(2,20)$'s $>2.21, P$'s <0.04] and a main effect of condition in the last two windows [$F(2,20)$'s $>6.78, P$'s <0.006]. Thus, we performed more focused comparisons for each time window to further characterize these effects. The results of the condition \times hemisphere ANOVAs for each location and time interval are shown in Table 2.

For the 150–300 ms interval, there was an overall effect of condition at frontopolar locations and condition \times hemisphere interactions at anterior–frontal, frontal and central locations. Follow-up contrasts revealed familiarity effects at both frontopolar sites [$t(10)$'s $>2.08, P$'s <0.05], but no recollection effects were observed during this window. In addition, there were no reliable familiarity or recollection effects at anterior–frontal, frontal or central locations. As can be seen in Fig. 7 this early familiarity effect had a very frontopolar topography.

For the 300–450 ms interval, main effects of condition were found at frontopolar, anterior–frontal and frontal sites. Follow-up contrasts revealed that familiarity [$t(10)$'s $>2.41, P$'s = 0.036] and recollection effects [$t(10)$'s $>2.15, P$'s <0.05] were reliable at the frontopolar sites, but not at anterior–frontal or frontal locations.

For the 450–600 ms interval, main effects of condition were found at all locations. Follow-up contrasts revealed no significant familiarity effects at any location, whereas recollection effects were observed at all locations in this time window [all $t(10)$'s $>2.64, P$'s <0.025]. As can be seen in Fig. 7, this recollection effect had a very widespread distribution in this time window.

Lastly, for the 600–800 ms interval, main effects of condition were found at frontopolar, frontal, central and parietal locations. Once again, follow-up contrasts revealed

Table 2

ANOVA results for retrieval phase ERPs as a function of subjects' memory judgments to old objects for main effect of condition and condition by hemisphere interactions

Location	Effect	Latency window (ms)							
		150–300		300–450		450–600		600–800	
		<i>F</i> (2,20)	<i>P</i>	<i>F</i> (2,20)	<i>P</i>	<i>F</i> (2,20)	<i>P</i>	<i>F</i> (2,20)	<i>P</i>
Frontopolar (FP1/FP2)	Condition	4.59	0.025	7.77	0.008	7.86	0.003	4.64	0.022
	Interaction	–	–	–	–	–	–	–	–
Anterior–frontal (AF3/AF4)	Condition	–	–	4.16	0.038	6.45	0.017	3.05	0.07
	Interaction	4.66	0.022	–	–	–	–	–	–
Frontal (F3/F4)	Condition	–	–	3.64	0.045	12.21	0.001	4.40	0.026
	Interaction	9.57	0.001	–	–	–	–	–	–
Central (C3/C4)	Condition	–	–	–	–	23.26	<0.0001	7.88	0.004
	Interaction	4.45	0.025	–	–	–	–	–	–
Parietal (P3/P4)	Condition	–	–	–	–	13.42	0.001	10.04	0.002
	Interaction	2.76	0.089	–	–	–	–	3.12	0.076

Note: Significant effects ($\alpha=0.05$) are shown in bold. Dashes represent *F*-values <1 and *P*-values >0.1 . †, Signifies that follow-up contrasts revealed significant familiarity effects. ‡, Signifies that follow-up contrasts revealed significant recollection effects.

Retrieval: Familiarity vs. Recollection

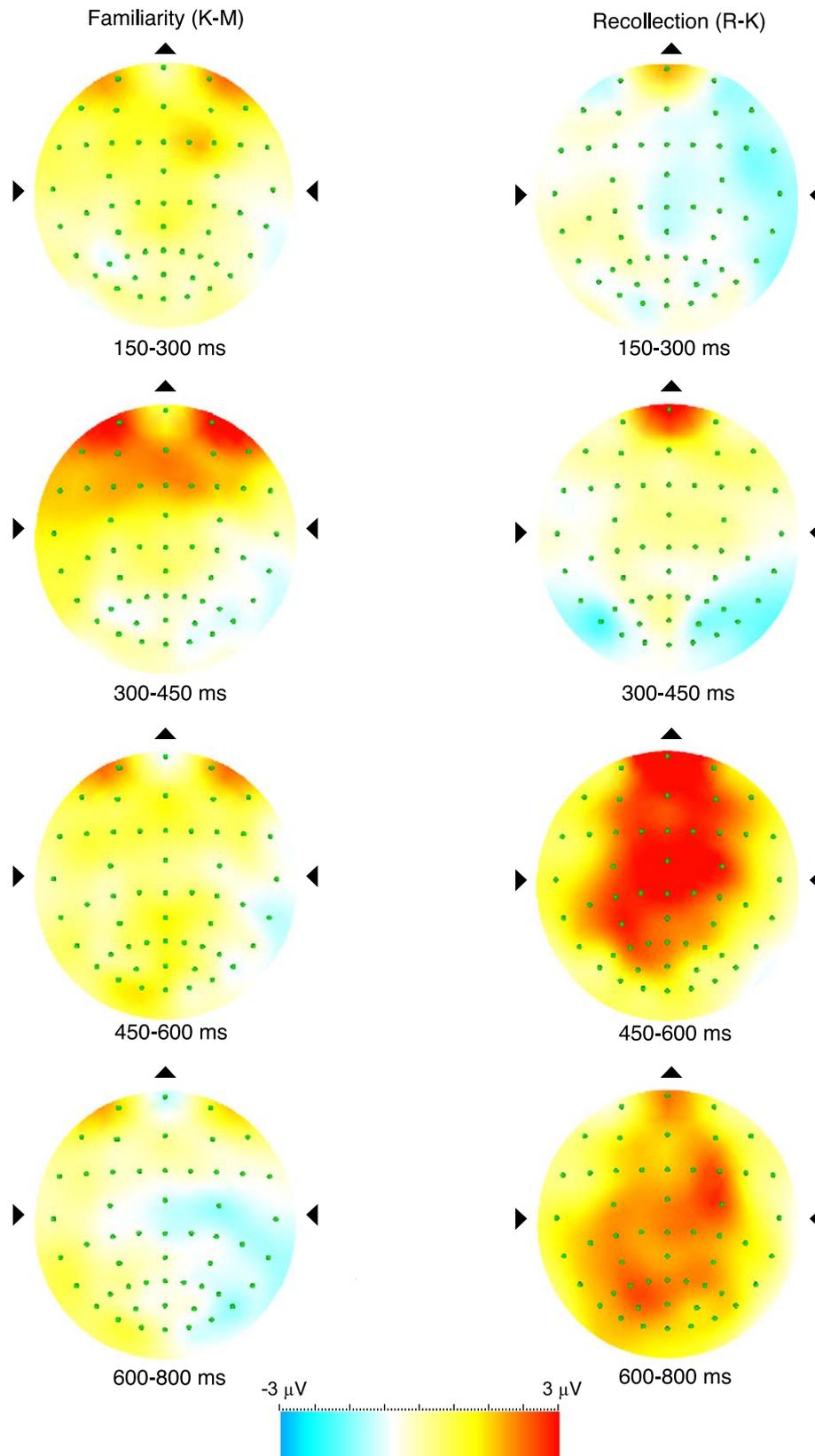


Fig. 8. Topographic maps depicting the time course of familiarity (K–M) and recollection (R–K) effects at test. Small circles represent electrode locations as viewed from above.

no reliable familiarity effects, but recollection effects were observed at frontal, central and parietal sites [all $t(10)'s > 2.17$, $P's < 0.05$], but not at frontopolar sites.

In summary, the above ERP analyses revealed neural correlates of familiarity and recollection during retrieval. A familiarity effect was reliable between 150 and 300 ms at frontopolar locations. Familiarity and recollection effects were found between 300 and 450 ms at frontopolar sites, and recollection effects were reliable at anterior sites from 450 to 600 ms and posterior sites from 450 to 800 ms.

3.2.5. Topographical comparisons of familiarity and recollection test effects

The scalp distributions for the familiarity (K–M) and recollection (R–K) test effects are shown in Fig. 8. Two types of topographical analyses were performed on the test phase ERP data. For the first analysis, we tested for topographic differences between ERP correlates of familiarity and recollection. We first tested whether these effects were topographically distinct in the 300–450 ms latency window, in which both effects were reliable. An ANOVA contrasting these effects gave no rise to the factor of condition but did reveal a main effect of location [$F(4,40) = 5.98$, $P = 0.01$]. As can be seen in Figs. 7 and 8, this reflects the frontopolar focus of these effects. We noted that the early frontopolar familiarity effect (150–300 ms) and the late parietal recollection effect (600–800 ms) that we observed bore strong functional, temporal, and topographic similarity to frontopolar and parietal old–new effects that were reported in a previous study [65]. Thus, we performed an analysis to determine whether these effects were topographically distinct. An ANOVA contrasting these effects revealed a location \times condition interaction [$F(4,40) = 2.74$, $P = 0.042$], reflecting the strictly frontopolar distribution of the familiarity and the more widespread frontal to parietal distribution of the recollection effect.

For the second analysis, we investigated whether the topographies of the familiarity and recollection effects changed over the latency windows in which reliable effects were observed. The ANOVA comparing the familiarity effect over the 150–300 ms and 300–450 ms windows revealed no effect of latency but a main effect of location [$F(4,40) = 3.12$, $P = 0.05$]. As can be seen in Figs. 7 and 8, this reflects the frontopolar focus of this effect in these two epochs. When the recollection effect was compared across the latencies in which it was reliable, 300–450, 450–600 and 600–800 ms, latency \times location [$F(8,80) = 8.09$, $P < 0.0001$], location \times hemisphere [$F(4,40) = 3.51$, $P = 0.041$] and latency \times location \times hemisphere [$F(8,80) = 4.11$, $P = 0.029$] interactions were found, reflecting a change in the distribution of this effect over time. An ANOVA contrasting the 300–450 and 450–600 ms recollection effects revealed latency \times location [$F(4,40) = 5.38$, $P = 0.005$], location \times hemisphere [$F(4,40) = 4.13$, $P = 0.029$] and latency \times location \times hemisphere [$F(4,40) = 3.91$, $P = 0.038$] interactions. As can be seen in Figs. 7 and 8, the

recollection effect was more widely distributed and had a left posterior maximum in the later time window. An ANOVA contrasting the last two epochs revealed a latency \times location [$F(4,40) = 5.71$, $P = 0.004$] interaction. As seen in the figures, the recollection effect was less robust in the latest epoch.

3.2.6. Summary of ERP results

In summary, distinct familiarity and recollection effects were observed during both encoding and retrieval. During encoding, a transient (300–450 ms) subsequent familiarity effect with a left-lateralized anterior scalp topography was observed. In addition, a topographically distinct subsequent recollection effect was observed between 300 and 600 ms. Although both of these effects exhibited similar onset times (at ca. 300 ms), they could be distinguished on the basis of topography and time course, supporting the idea that familiarity and recollection processes exhibited distinct neural correlates during encoding.

During retrieval, an early onset familiarity effect was observed at frontopolar sites from 150 to 300 ms. During the 300–450 ms, ERPs at frontopolar sites differentiated recollected, familiar, and missed items in a graded manner. Finally, a sustained recollection effect was observed from 300 ms until the end of the recording epoch and observed maximally at left posterior sites, where no familiarity effects were seen. The early frontopolar familiarity effect and the late occurring recollection effect could be functionally, temporally, and topographically differentiated, suggesting that recollection and familiarity exhibited distinct neural correlates at retrieval.

4. Discussion

The purpose of this experiment was to identify and potentially dissociate neural signals associated with two forms of declarative memory, familiarity and recollection. The temporal resolution of the ERP method allowed us to additionally characterize the time course of these neural signals. Specifically, we recorded neural activity at encoding and retrieval and correlated these measures with separate indices of recollection and familiarity. Our results revealed that recollection and familiarity had distinct neural signatures at the time of encoding and retrieval. At the time of encoding, neural correlates of familiarity and recollection appeared to onset in parallel, whereas at the time of retrieval, correlates of familiarity emerged earlier than did correlates of recollection. We discuss these results and their implications in more detail below.

4.1. Distinct correlates for recollection and familiarity at encoding

As observed in numerous studies, we observed positive modulations in ERPs at frontal scalp sites during encoding

that differentiated subsequently recognized from subsequently missed items. In the present study, we further characterized whether distinct ERP correlates for subsequent memory could be observed for familiarity and recollection. These effects are summarized in Fig. 9. As shown in the graph, a left-lateralized, anteriorly distributed subsequent familiarity effect was apparent in the 300–450 ms time window. A temporally overlapping, but topographically distinct subsequent recollection effect was also observed at right anterior locations from 300 to 450 ms and bilaterally but still with a stronger right focus between 450 and 600 ms.

Although the subsequent familiarity and recollection effects we observed both had a frontal topography and similar onset times, several considerations suggest that these two effects reflected qualitatively different patterns of activity. First, during the 300–450 ms window, when both effects were significant, topographical differences between these effects were reliable after rescaling [40,51]. Although some debate exists as to the precise inferences that can be drawn from topographical analyses of rescaled ERPs [67], these concerns do not preclude the interpretation that recollection and familiarity exhibited different neural correlates at encoding.

Some previous ERP studies have attempted to dissociate familiarity and recollection during encoding without success [20,60]. However, in one study by Mangels et al. [37], left-lateralized frontal activity occurring between 300 and 400 ms was elicited by all subsequently recognized items and not sensitive to recollection while bilateral frontal activity between 1000 and 2000 ms was predictive of recollection, although the topographies of the effects were not extensively characterized. This finding supports our own and suggests that transient frontal activity was sufficient to produce subsequent familiarity but not recollection, which necessitated more extensive processing.

Converging evidence comes from numerous neuropsychological [2,13,75] and functional neuroimaging [6,12,18,50] studies showing dissociations between familiarity and

recollection. For example, in a recent event-related fMRI study [50], we demonstrated that increased activity in the left rhinal cortex predicted subsequent familiarity-based recognition (as indexed by subsequent recognition confidence judgments), whereas right hippocampal and parahippocampal activity predicted subsequent recollection (as indexed by subsequent source memory accuracy). These data collectively support our assertion that the neural correlates we observed for familiarity and recollection do indeed reflect dissociable patterns of brain activity emerging from different neural substrates.

Finally, the lateralized activity we observed during encoding may, in part, be related to the type of stimulus material. As most previous encoding studies have used verbal stimuli, it may be that the pictorial images we used in the present study may account for some of the lateralized effects. For example, some fMRI studies have shown that lateralized activity during encoding may shift hemisphere depending on the stimulus material [32,68]. In these studies, pictorial stimuli often elicit right-lateralized or bilateral frontal activity while words elicit left-lateralized activity. Further research comparing correlates of memory formation for different types of materials will be necessary to determine whether the topographies of the recollection and familiarity effects observed here would be material-dependent.

4.2. Correct rejections versus misses at retrieval

As has been reported in some previous studies [65,70], old items misclassified as new (M) did not differ reliably from CR new items. One previous study has shown that unrecognized old items differ from new item ERPs during retrieval, despite lack of conscious recollection [54]. Differences between the experimental methods used in the aforementioned study and our own, which may account for the discrepancy. For example, in the present study, stimulus presentation duration was much less (180 ms) than that of

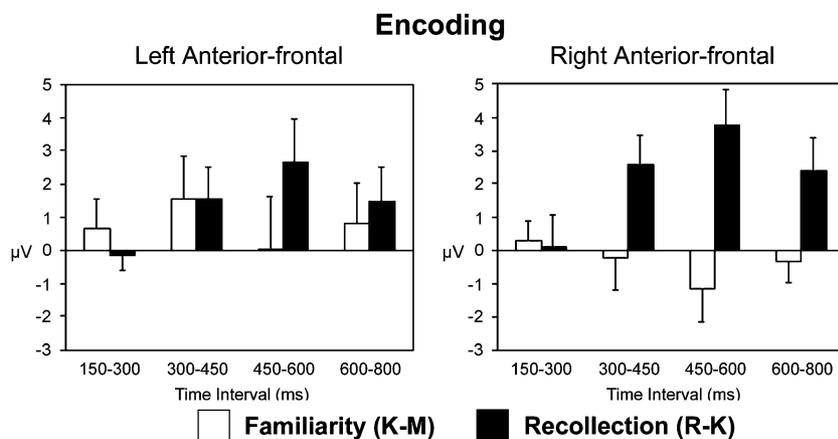


Fig. 9. Summary of subsequent familiarity (K–M) and subsequent recollection (R–K) effects at encoding. Effects are shown at left and right anterior–frontal sites. S.E.M. bars are shown.

(300–500 ms) Rugg et al. [54]. Thus, it may be that in the present study, missed old items were not sufficiently processed during encoding in order to yield old–new effects during retrieval.

4.3. Dissociable correlates for recollection and familiarity at retrieval

Consistent with results from previous ERP studies, our results showed that ERPs at retrieval were sensitive to varying degrees of successful retrieval. We further characterized these effects as related to familiarity and recollection. As shown in Fig. 10, a familiarity effect was apparent between 150 and 300 ms at frontopolar locations. Overlapping familiarity and recollection effects were observed at these locations between 300 and 450 ms. Recollection effects were seen at anterior locations from 450 to 600 ms and at posterior locations between 450 and 800 ms.

Overall, these findings suggest that neural correlates of familiarity onsetted earlier than did neural correlates of recollection at the time of retrieval. Thus, the familiarity and recollection effects we observed during retrieval were both temporally and topographically separable. This fits well with numerous behavioral studies showing that familiarity is typically faster than recollection (see [72] for review). For example, recognition studies which have required speeded response time decisions have determined that item recognition accuracy increases earlier than source recognition accuracy, supporting the idea that familiarity is faster than recollection (e.g. [27,29]).

The early frontopolar effect seen in the current study dissociated recognized from missed studied items, beginning as early as 150 ms. This effect is strikingly similar in both latency and topography to an old–new effect first described by Tsivilis et al. [65]. In that study, all correctly identified test items that contained at least one studied component elicited positive deflections relative to new items. Because this effect had not previously been reported,

Tsivilis et al. [65] performed a second, very similar, experiment in which the frontopolar effect was replicated. Based on these results, Tsivilis et al. concluded that the frontopolar old–new effect was a robust correlate of item repetition, but it was unclear whether this effect was best described as a neural correlate of familiarity-based recognition, or whether it reflected a correlate of perceptual priming that was unrelated to successful recognition.

In the current study, all correctly recognized items, regardless of whether they were associated with R or K judgments, elicited an enhanced frontopolar effect relative to missed items but R and K items did not differ from one another. Under the assumption that perceptual priming was relatively equivalent for missed and recognized items, this pattern of results suggests that the frontopolar old–new effect is specifically related to familiarity-based recognition. As noted by Tsivilis et al. the timing of the frontopolar effect coincides well with results from single unit studies showing rapid familiarity responses less than 100 ms post-stimulus onset during retrieval in the perirhinal cortex of rats and monkeys (see [7] for review). Although the time course of these familiarity signals are similar to that latency of the frontopolar effect in the present study, the spatial limitations of ERP preclude definitive localization of the effect.

Between 300 and 450 ms, we identified a negative-going wave that differentiated recollected, familiar, and missed items. The latency and frontal topography of this effect suggest that it may be related to the “FN400 old–new” effect, which onsets at approximately 400 ms at frontal sites, although typically less anterior than the frontopolar focus we have observed (see [19] for review), which could be the result of low statistical power at other frontal locations. Previous studies have shown that this effect is insensitive to recollection, in that it only dissociated items based on whether they were correctly identified as old or new [60,63] or by how similar test items were to studied ones [11,65]. Additionally, one study, which also used the remember–know procedure, showed no distinction in the

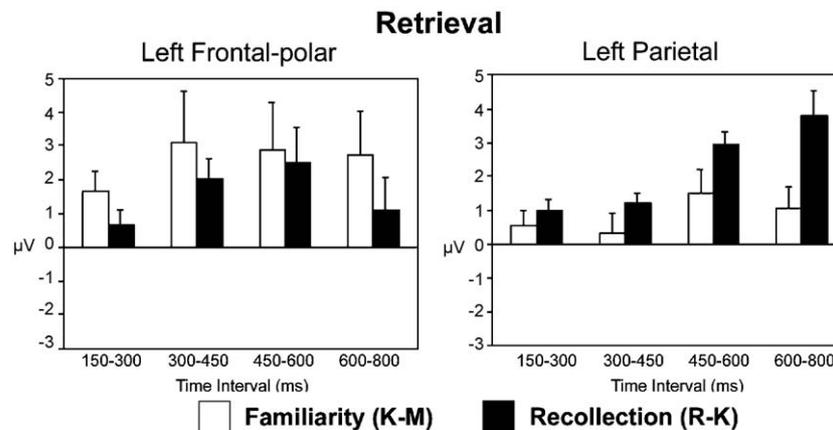


Fig. 10. Summary of familiarity (K–M) and recollection (R–K) effects at retrieval. Effects are shown at left frontopolar and parietal sites. S.E.M. bars are shown.

FN400 between remembered and known items [60], in contrast to what we have shown here.

The findings from the 300 to 450 ms time window are open to a number of potential interpretations. One possibility is that, in contrast to previous results, the putative FN400 old–new effect observed here was not purely reflective of familiarity based-recognition, but instead reflected a graded index of successful memory retrieval. Alternatively, the effect seen in the present study could be the result of neurally distinct, but temporally overlapping familiarity and recollection effects during this time window. In the absence of significant topographical differences between familiarity and recollection effects during this window, we cannot adjudicate between these two hypotheses. Further research using strong manipulations of recollection and familiarity will be necessary in order to determine whether FN400-like effects are specifically related to familiarity-based recognition.

Between 600 and 800 ms, ERP correlates of recollection were apparent over left posterior sites, existing as an enhanced positive deflection for R compared to K and M items. Based on its timing and topography, this effect bears strong similarity to the parietal old–new effect observed in previous studies of recognition memory [48,62]. It has been suggested that this effect is a neural correlate of conscious recollection [14,44,49]. Consistent with this view, several studies using the “remember–know” paradigm [60,64], have demonstrated that this effect is larger in magnitude for R than for K items.

An alternate interpretation of the parietal old–new effect is that it more generally reflects the amount of information that is successfully retrieved, given that recognized items that are not completely recollected often elicit a weak parietal old–new effect. For example, some previous ERP studies have shown that this left effect was largest for recollected items but also reliable for items recognized solely on the basis of familiarity in both R/K [60,64] and source [63,70,71] decision studies. These data suggest that the parietal effect represents a graded continuum of recognition. However, it has also been suggested that the parietal old–new effect reflects a graded continuum that is specific to recollection, as the effect covaries with the amount of source information retrieved [69].

In the present study, the parietal old–new effect was strongly and specifically related to recollection. We observed a robust parietal effect for R items but no reliable difference was found between K and M items. This supports the idea that the parietal old–new effect represents a neural correlate of recollection (see [30,52] for reviews). Another study, which also used the “remember–know” paradigm, demonstrated a similar finding [14]. Thus, only recollected items necessitated extensive processing, beyond the early frontal activity that was sufficient to engender a feeling of familiarity but not of recollection.

Results from some event-related fMRI [8,25,35] studies of recognition memory suggest that the parietal old–new

effect may reflect the activity of underlying regions in left parietal cortex. For example, as reviewed by Buckner and Wheeler [8], activity in the left superior and inferior lateral parietal cortex is commonly correlated with successful retrieval in episodic memory tasks. Furthermore, in one recent event-related fMRI study using the “remember–know” paradigm, left inferior and superior parietal regions exhibited greater activity for R than for K items [25], lending further support to the idea that parietal activity may be associated with the parietal old–new ERP effect observed here. However, another recent study has suggested that activation in the medial but not lateral parietal regions may be specifically related to memory retrieval [9]. Thus, further studies will be necessary to allow for more definitive conclusions regarding the role of parietal cortex in memory retrieval.

In addition to the parietal cortex, ERP studies [13,41,55,61] of patients with medial temporal lesions suggest that this region may also contribute to the parietal old–new effect. For example, studies of patients with large medial temporal lesions due to excision [55,61] have shown that the parietal old–new effect was impaired or absent in these patients. Although the patients in these studies had medial temporal lesions which extended beyond the hippocampus, other ERP studies have shown that patients with focal hippocampal lesions also had impaired parietal effects [13,41]. It is unlikely that scalp-recorded old–new effects directly reflect volume-conducted hippocampal field potentials (see [42] for review). Nonetheless, these findings suggest that the hippocampus may be essential for the generation of the parietal old–new effect.

4.4. No evidence for lateralization of visual memory representations

Another objective of the present study was to determine whether lateralized stimulus presentation might result in lateralized memory representations. In contrast to results from a previous study by Gratton et al. [24], we found no evidence of enhancement of memory-related effects either at encoding or retrieval over the hemisphere contralateral to initial stimulus presentation. In the study by Gratton et al. [24], abstract visual images were laterally presented during encoding and centrally presented during retrieval. ERPs recorded during the retrieval phase were enhanced at posterior locations over the hemisphere contralateral to stimulus presentation during encoding. It was concluded that memory representations may be organized in a lateralized fashion.

One possible explanation for the discrepancy between our results and those reported by Gratton et al. [24], is that perhaps stimulus presentation during encoding was not sufficiently lateralized to effectively promote lateralized memory representations. However, investigation of left versus right-presented stimulus ERPs revealed enhanced early visually evoked potentials over the contralateral hemisphere during encoding. Contralateral enhancements in

these early visually evoked potentials are typical when stimuli are presented in a lateralized fashion (see [26,38] for review). Thus, despite the fact that stimulus presentation in this experiment produced lateralized visual processing at encoding, no evidence for lateralized memory effects were observed at either encoding or retrieval.

There are a number of methodological differences between the study by Gratton et al. [24] and our own. For example, in their study abstract visual line patterns were used whereas we used concrete visual objects. The items in our study were most likely familiar to participants, even though the actual images were novel. Thus, memory representations may have already existed for these stimuli even before subjects encoded them and lateralization of processing could not have been controlled. Support for this hypothesis comes from the findings of Biederman and Cooper [5] who showed no evidence of a same hemifield enhancement for the memory of namable objects, which has been shown for abstract visual images in other studies (e.g. [3,24]). Although one study did show lateralized retrieval effects for words [17], it may be that laterally-presented words and pictures differ in their retrieval representations. Further studies directly contrasting words and pictures may be necessary to determine whether lateralized study presentation differentially affects their retrieval representations.

Another very important difference between the two studies concerns the method of analysis of retrieval ERPs. Gratton et al. [24] contrasted only old item ERPs (left vs. right visual field) in order to determine whether memory was lateralized during retrieval. In fact, when old items were compared with new item ERPs, “old–new” effects were not observed. Thus the conclusions drawn by Gratton et al. [24] that visual memories are organized in a lateralized fashion may not be extendable to typical memory retrieval effects.

4.5. Neural mechanisms for familiarity and recollection

In conclusion, results from the present study support the notion that measures of familiarity and recollection reflect the outcome of neurally dissociable processes both during encoding and retrieval. Taken along with recent functional neuroimaging [12,25,50] and neuropsychological [75] results, these data suggest that recollection and familiarity are supported by different types of neural representations. Future research utilizing the parallel application of ERP, hemodynamic and neuropsychological methods will allow for a more definitive characterization of the neural mechanisms for familiarity and recollection.

Acknowledgements

This research was supported by NINDS grants NS21135 and (program project) PO1 NS40813 and the Veterans Administration Research Service.

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