Published in final edited form as:

Psychophysiology. 2009 January ; 46(1): 86–99. doi:10.1111/j.1469-8986.2008.00754.x.

Effects of multiple study-test repetition on the neural correlates of recognition memory: ERPs dissociate remembering and knowing

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Abstract

ERP frontal (300–500 ms) and parietal (500–700 ms) episodic memory (EM) effects are thought to reflect, respectively, familiarity and recollection. However, as most ERP studies use pre-experimentally familiar items, an alternative idea is that the frontal EM effect reflects conceptual priming. Repetition of unnameable symbols was used to assess modulations of the putative ERP indices of familiarity and recollection. The same symbols were viewed in each of 4 study/test blocks. Increases in familiarity and conceptual processing of symbols did not modulate the frontal EM effect, suggesting that it reflects neither familiarity nor conceptual priming. The magnitude of the parietal EM effect increased and its onset latency decreased across tests for items given remember (R), but not know (K) judgments. R and K old-new topographies differed. These findings support dual-process proposals that familiarity- and recollection-based processes are distinct.

Introduction

According to dual-process models, successful recognition memory performance is contingent upon two qualitatively dissociable neurocognitive processes: familiarity and recollection (Jacoby & Dallas, 1981; Mandler, 1980; Tulving, 1985; for a review, see Yonelinas, 2002). Familiarity-based recognition is considered to be an acontextual, automatic and fast acting quantitative assessment of memory strength. In contrast, recognition supported by recollection is thought to involve the relatively slow and controlled retrieval of contextual information associated with a previous encounter of the recognized item (i.e., an item's source).

Evidence supporting the idea that processes of familiarity and recollection are qualitatively distinct has been found at a neural level from a variety of sources, including rodent and primate studies (Brown & Aggleton, 2001; Fortin, Wright, & Eichenbaum, 2004), patient studies (Holdstock et al., 2002; Yonelinas et al., 2002), functional magnetic resonance imaging or fMRI investigations (Eldridge, Knowlton, Furmanski, Bookheimer, & Engel, 2000; Yonelinas, Otten, Shaw, & Rugg, 2005) and ERP studies (Curran, 2000; Rugg et al., 1998). ERPs, in particular, provide an ideal method to investigate dual-process models because distinct ERP effects have been identified as indices of familiarity and recollection (for reviews, see Donaldson, Wilding, & Allan, 2003; Friedman & Johnson, 2000; Rugg & Yonelinas, 2003).

These ERP effects take the form of differences in the waveforms for correctly identified old (i.e., previously studied) items relative to correctly identified new (i.e., previously unstudied) items and will be referred to here as episodic memory (EM) effects. Familiarity is associated with an enhanced positivity for correctly identified old items, maximal over frontal sites between approximately 300–500 ms post-stimulus – this modulation is known as the frontal EM effect. Recollection is thought to be indexed by an enhanced positivity for correctly identified old items, maximal over parietal sites between 500–700 ms post-stimulus – this effect is referred to as the parietal EM effect.

Various lines of evidence support the relation between the parietal EM effect and recollection. For example, it is larger in association with correctly recognized old items given remember judgments, (i.e., those for which some contextual detail has been recovered) compared to those given know judgments (i.e., those based on a sense of familiarity only) (e.g., Trott, Friedman, Ritter, Fabiani, & Snodgrass, 1999; Vilberg, Moosavi, & Rugg, 2006). The parietal EM effect is also larger for words for which the source is correctly, rather than incorrectly, retrieved (e.g., Curran, 2000) and is absent, or greatly attenuated, in patients who have a selective impairment in the ability to recollect information (Duzel, Vargha-Khadem, Heinze, & Mishkin, 2001; Tendolkar et al., 1999). Evidence supporting an association between the frontal EM effect and familiarity, however, is arguably less consistent than that supporting the link between the parietal EM effect and recollection. Processes underlying familiarity are thought to respond to the overall similarity between studied and test items (e.g., Gillund & Shiffrin, 1984; Hintzman & Curran, 1994). Thus, findings that the frontal EM effect is elicited by correctly identified old items as well as false alarms to perceptually similar new items (e.g., Curran, 2000; Nessler, Mecklinger, & Penney, 2001), but is not elicited by misses, support the notion that this effect is a neural correlate of familiarity-based recognition.

Very few studies have investigated EM effects for pre-experimentally unfamiliar stimuli (i.e., stimuli that have no pre-existing semantic representations). Of those that have, there are a number of inconsistencies with regard to the elicitation of the frontal EM effect. Two recent ERP studies using unfamiliar faces report discrepant findings (Curran & Hancock, 2007; MacKenzie & Donaldson, 2007). In the Curran and Hancock study, frontal EM effects were found for recollected old items as well as old items recognized on the basis of familiarity, whereas MacKenzie and Donaldson reported frontal EM effects for recollected old items only (see Donaldson & Curran, 2007, for comment). Yovel and Paller (2004) also reported an absence of frontal effects for repeated, pre-experimentally non-familiar faces, despite the fact that participants indicated familiarity (via ‘know’ responses) for these stimuli within the experimental context. Given that frontal EM effects have generally been reported for items that have a great deal of pre-experimental familiarity (e.g., nameable pictures, words), findings from two of these studies using novel faces indicate that the frontal EM effect may not, in fact, be a pure index of experimental familiarity processing. One possibility is that this effect may reflect an interaction between pre-experimental and experimental familiarity (Greve, van Rossum, & Donaldson, 2007; Nessler, Mecklinger, & Penney, 2005). Yovel and Paller have further suggested that the frontal EM effect may not index an explicit memory process at all but may instead reflect a reduction of the N400 component. This latter component has been mainly studied within the context of psycholinguistic research and is known to be modulated by the ease with which the meaning of words can be integrated into a given context (see Kutas & Federmeier, 2000, for a review). Given this view, rather than reflecting familiarity, the frontal EM effect could reflect verbally-mediated conceptual priming.

There are, however, two reports of frontal EM effects for novel visual patterns (Curran, Tanaka, & Weiskopf, 2002; Van Petten & Senkfor, 1996). Given that these stimuli had no pre-existing semantic representations and, thus, were unlikely to have been conceptually processed at test, these findings seem inconsistent with Yovel and Paller’s proposal that the frontal EM effect

reflects conceptual priming. However, it has been pointed out that the multiple exposure of novel patterns during the study phase in these latter two studies may well have encouraged the semantic encoding of studied items (Groh-Bordin, Zimmer, & Ecker, 2006). Furthermore, although Groh-Bordin et al. (2006), in their study, reported a frontal EM effect for old nonsense figures after just one repetition, the stimuli employed in this study have since been found to vary in subjective measures of meaningfulness across individual participants (Voss & Paller, 2007). Thus, while any one particular ‘nonsense’ figure may seem meaningless to some participants, the same item may be meaningful to others. Using these individual measures of meaningfulness, in contrast to Groh-Bordin et al.’s findings, Voss and Paller reported that the magnitude of the EM frontal effect was larger for figures given high, compared to low, meaningfulness ratings. These latter findings support the idea that the frontal EM effect may be more closely related to conceptual priming than to familiarity.

Here, we also used unfamiliar and unnamable symbol-like stimuli to investigate modulations of the putative ERP correlates of familiarity and recollection by the learning engendered through multiple study and test repetitions. Young adults memorized the same 40 items which they viewed in each of 4 study/test blocks – new items differed for each test (cf. Johnson, Kreiter, Russo, & Zhu, 1998). Therefore, the present study provides a unique opportunity to determine how the recognition of pre-experimentally unfamiliar symbols at test modulates frontal and parietal EM effects across multiple study-test repetitions. Study items were always presented in the same spatial location (left/right of fixation) and old/new, source (location) and remember/know judgments were solicited. In line with previous findings (e.g., Jacoby, Jones, & Dolan, 1998), we expected both familiarity and recollection to increase with study repetition. Thus, if frontal and parietal EM effects reflect, respectively, familiarity- and recollection-based recognition, we expected both EM effects to increase in amplitude across tests. A final ‘symbol naming’ task also enabled us to determine, for each participant, which of the 40 old symbols had, in fact, been conceptually processed. This allowed us to assess the potential impact of implicit conceptual priming on the magnitude of the frontal EM effect. If the frontal EM effect is related to conceptual priming, then the magnitude of this effect should be greater for repeated items that had been conceptually processed than for those that had not.

Method

Participants

Twenty six right-handed young adults participated in this experiment, all of whom spoke English as their first language. Data from 8 participants were discarded, 7 due to an insufficient number of artifact-free trials in one or more of the critical conditions, and one other for not following experimental instructions. Of the remaining 18 participants, 16 were female, and their ages ranged between 21 and 25 years (mean age: 23 years). The study was approved by the Institutional Review Board of the New York State Psychiatric Institute. All participants gave informed consent before taking part in this experiment and were reimbursed at the rate of \$10.00 per hour.

Stimuli

To assess the effects of study-test repetition on the putative ERP correlates of familiarity and recollection, we created study and test lists that were to be repeated four times as studied (old) items but employed different lists of unstudied (new) items for each test list. Critical stimuli consisted of 160 unfamiliar symbols, each of which was determined to be initially unnameable from the ratings of at least 8 out of 10 pilot participants. From this pool of 160 symbols, 4 lists of 40 symbols were randomly chosen to be rotated across participants so that each list served approximately equally often as the study list. Thus, for each participant, the 4 study lists contained the same 40 symbols, although the symbols were randomly ordered for each study.

From the remaining pool of 120 symbols, 4 test lists were randomly assigned 30 symbols each to serve as new items. Each of the 4 test lists additionally contained the 40 old symbols that had been presented during study. Thus, each test list contained 70 symbols which were randomly ordered for each participant. There were 4 additional filler symbols, of which 2 were added to the beginning and 2 were added to the end of the study list. These 4 fillers were not analyzed.

Procedure

After Electrocap placement (see 'ERP recording and analysis'), participants were seated in a sound damped and electrically shielded room approximately 100 cm from a 17" display monitor on which the experimental stimuli were presented. They held a response box on their laps. Participants were informed that they would be taking part in a memory experiment consisting of 4 study/test blocks (each study phase was followed by a test phase) and were given instructions for the Remember/Know procedure (Tulving, 1985). Instructions for this procedure were comprehensive and based on those used in previous research (Gardiner, 1988). After finishing all 4 study/test blocks, participants completed a debriefing questionnaire and then a 'symbol naming' task in which the 40 old symbols were re-presented one at a time on the computer screen. For each of these symbols, participants were asked if it had reminded them of a familiar object and/or if they had 'named' this symbol at any point during the experiment. There were no time constraints for this part of the experiment and the experimenter recorded participants' responses verbatim.

All stimuli were presented in black outline within a centrally-located grey presentation box (500 × 500 pixels). Half of the study stimuli were presented to the left, and half to the right, of center. Symbol-to-side of presentation mapping was randomly assigned, but remained invariant for each of the 4 study phases. For each experimental block, study and test phases were participant-initiated by pressing a response button when the instruction, 'Press When Ready', appeared on the screen. This was followed by a blank presentation box for 1000 ms. Study and test trials consisted of the presentation of the stimulus for 500 ms, followed by a blank presentation box for 1500 ms. Participants rested their index fingers on the corresponding left- and right-hand buttons of the response box. For the purposes of EEG recording, participants were asked to relax, fixate their gaze at the center of the screen, avoid all eye movement and keep their blinking to a minimum.

Figure 1 provides an overview of the design. For each study phase, participants were asked to memorize each symbol and its associated side of presentation (left or right) for a subsequent memory test. In order to ensure that they attended to the side of presentation, participants were required to press the corresponding left- or right-hand button during stimulus presentation. For each trial during the test phase, the requirement was to press one button for symbols that had been presented during the study phase (i.e., old symbols) and the other button for new symbols. The mapping of hand to old/new response was rotated across participants and study list assignment. When a participant responded 'new', the next symbol was presented. However, when an old response was indicated, participants were required to make two more judgments. One of these was a Remember/Know (R/K) judgment which was cued by one of two types of display: 'Remember ? Know' or 'Know ? Remember'. The type of R/K cue was invariant for each participant but was rotated across participants, study list assignment and old/new response. Participants were also required to decide if the symbol had been presented to the left or right of fixation during study, and the cue for this source judgment was indicated on the computer screen by the instruction 'Left ? Right'. Participants indicated their choice by pressing the response button on the side indicated by the corresponding prompt. In order to prevent early anticipatory responses, the Left/Right and R/K cues were randomly ordered. For all study and test trials, participants were asked to respond as quickly and accurately as possible – any

responses faster than 300 ms or slower than 2000 ms were rejected and not included in the analyses. All participants received a short study-test practice block prior to commencing the first experimental block.

ERP recording and analyses

EEG was recorded with sintered Ag/AgCl electrodes mounted in an elastic cap (Neuromedical Supplies) from 62 scalp sites in accordance with the extended ten-twenty system (Sharbrough et al., 1990). Participants were grounded with an electrode placed on the right forehead. Horizontal EOG was recorded from electrodes placed on the outer canthus of each eye and vertical EOG was recorded from electrodes placed above and below the left eye. Electrode impedance was kept below 5 kOhms. Eye movement artifacts were corrected off-line (Semlitsch, Anderer, Schuster, & Presslich, 1986) and trials with other visible artifacts (e.g., muscle artifacts) were rejected. The activity at all scalp electrodes was recorded referenced to the nose tip and re-referenced offline to averaged mastoids. EEG and EOG (DC; 100 Hz high-frequency cut-off; 500 Hz digitization rate) were recorded continuously with Synamp amplifiers. Data were epoched off-line with 100 ms pre- and 1900 ms post-stimulus intervals (the pre-stimulus interval served as the baseline). ERP averages were formed for correct responses to both old and new items associated with each of the four tests. The number and range of trials contributing to the averaged ERPs for each set of analyses are shown in Table 1A–H.

Results

Behavioral and ERP data were analyzed using repeated measures ANOVAs (alpha level = .05). F-ratios are reported with uncorrected degrees of freedom, corrected p-values and the epsilon (ϵ) value calculated to correct for non-sphericity (Greenhouse & Geisser, 1959). As we were expecting monotonic changes across the 4 tests, whenever a main effect of Test was obtained for a particular variable, this was followed up with a trend analysis in order to explore whether a polynomial function might fit the data.

Old/new recognition

Behavioral data—To assess changes in behavioral performance across the 4 tests, old-new discrimination ($Pr: P_{hit} - P_{false\ alarm}$) and response bias ($Br: P_{false\ alarm} / 1 - (P_{hit} - P_{false\ alarm})$) indices (Snodgrass & Corwin, 1988) were computed separately for each test. These measures, along with old and new item accuracy and reaction time (RT) performance (for correctly identified items only), are summarized in Table 2. Pr and Br were subjected to one-way ANOVAs employing the factor of Test (1, 2, 3, 4). These gave rise to main effects of Test ($Pr: [F(3,51) = 80.15, p < 0.001]$; $Br: [F(3,51) = 13.71, p < 0.001]$), reflecting a linear increase in discrimination accuracy [$F(1,17) = 240.02, p < 0.001$] and response bias, i.e., from conservative to more liberal responding, [$F(1,17) = 41.97, p < 0.001$] across the four tests. Given the numerical decrease in false alarms alongside increased hits across tests (see Table 2), this increase in liberal responding merely reflects the improvement in old-new discrimination. Trend analysis revealed an additional quadratic component for Pr [$F(1,17) = 24.61, p < 0.001$], reflecting the fact that this increase in discrimination accuracy begins to level off by Test 4.

In order to assess the ease with which test items were processed, and to determine whether this changed with each test repetition, RTs to correctly identified old and new items in each test were analyzed with an ANOVA employing the factors of Test and Item Type (old, new). This analysis gave rise to a main effect of Test [$F(3,51) = 11.01, p < 0.001, \epsilon = 0.65$], but no significant interaction between Item Type and Test, reflecting, collapsed across old and new items, a linear decrease in RTs over the four tests [$F(1,17) = 19.50, p < 0.001$].

To summarize the behavioral results, across test repetitions, old-new discrimination improved and responses to correctly identified old and new items became increasingly faster.

ERP data—Grand average waveforms from 6 representative scalp locations (F3, Fz, F4, P3, Pz, P4) associated with correct responses to old and new items for the four tests are depicted in Figure 2. As expected, this figure shows that correctly identified old items elicit more positive-going ERPs than correctly rejected new items over frontal and parietal electrode sites from around 200–300 ms post-stimulus, an effect which, over frontal electrode sites, lasts until the end of the epoch. Figure 3 shows that the scalp distribution of these effects appears to differ as a function of time and, particularly in the 300–500 ms latency region, as a function of test repetition. These effects appear to be maximally distributed over frontal sites during the 300–500 ms latency region for Test 1, but become more posteriorly distributed with each test repetition during the same latency region. For the 500–700 ms latency region, these effects appear to be maximally distributed over mid- and left parietal sites in all tests, characteristic of the parietal EM effect associated with recollection reported in previous research (Friedman & Johnson, 2000).

ERP waveforms associated with correctly identified old and new items in each test were quantified by measuring the mean amplitude (relative to the pre-stimulus baseline) over two consecutive latency regions: 300–500 ms and 500–700 ms. ERP analyses were conducted on data from 10 electrode sites, including 5 frontal sites (F3, F1, Fz, F2, F4) and 5 parietal sites (P3, P1, Pz, P2, P4) which were factored according to anterior-posterior chain or ‘AP’ (anterior, posterior) and sagittal plane or ‘SP’ (left mid-lateral, left superior, midline, right superior, right mid-lateral). The selection of these latency regions and electrode sites was based on previous findings, as well as visual inspection of the waveforms in the present experiment, in order to capture frontal and parietal EM effects associated, respectively, with familiarity and recollection. Initial ANOVAs were conducted in order to establish if reliable EM effects were obtained for each test. These employed the factors of Item Type (old, new), AP and SP and were conducted on data from each latency region of interest (i.e., 300–500 ms and/or 500–700 ms). In order to determine whether the magnitudes of frontal and/or parietal effects were influenced by test repetition, we directly contrasted these effects using the difference scores (i.e., old minus new) between tests. Follow-up comparisons were performed whenever interactions with AP and/or SP were obtained. Measures of treatment magnitude (Keppel, 1991) are given to enable comparison of the magnitudes of any obtained EM effects at different locations.

Analyses of EM effects within each test

300–500 ms latency region—The initial ANOVA for Test 1 gave rise to a main effect of Item Type [$F(1,17) = 16.98, p < 0.001$] reflecting greater positivity for old than new items. There was also an interaction between Item Type and AP [$F(1,17) = 7.50, p < 0.05$] indicating that, while this positivity was significant over both anterior and posterior locations as revealed by follow-up tests [$F_s > 9.64, p_s < 0.01$], it was greater over anterior ($\omega^2 = 0.46$) than posterior ($\omega^2 = 0.32$) sites. In contrast, only main effects of Item Type were revealed for Tests 2 [$F(1,17) = 20.67, p < 0.001$] and 3 [$F(1,17) = 33.69, p < 0.001$], reflecting a positivity which was more evenly distributed over the anterior/posterior plane. In test 4, the initial analysis gave rise to a main effect of Item Type [$F(1,17) = 35.83, p < 0.001$], reflecting greater positivity for old than for new items. In addition, there were interactions between Item Type and AP [$F(1,17) = 6.59, p < 0.05$], and Item Type and SP [$F(4,68) = 5.23, p < 0.01, \varepsilon = 0.68$]. While follow-up comparisons revealed that this positivity was significant at anterior and posterior locations [$F_s > 26.96, p_s < 0.001$] as well as at all sagittal locations [$F_s > 30.20, p_s < 0.001$], the interactions reflect the fact that this effect is larger over posterior sites ($\omega^2 = 0.63$) than over anterior sites

($\omega^2 = 0.59$), and greater over superior sites (right and left: $\omega^2 = 0.67$) than over all other sagittal locations (left mid-lateral: $\omega^2 = 0.62$; mid-line: $\omega^2 = 0.64$; right mid-lateral: $\omega^2 = 0.64$).

500–700 ms latency region—Initial ANOVAs revealed main effects of Item Type for Test 1 [$F(1,17) = 32.59$, $p < 0.001$], Test 2 [$F(1,17) = 39.42$, $p < 0.001$], Test 3 [$F(1,17) = 37.78$, $p < 0.001$] and Test 4 [$F(1,17) = 24.82$, $p < 0.001$], indicating greater positivity for old than for new items. For Test 4, however, an additional interaction between Item Type and AP [$F(1,17) = 11.13$, $p < 0.01$] indicated that, although significant at both anterior and posterior locations [$F_s > 12.58$, $p_s < 0.01$], this effect was greater over parietal ($\omega^2 = 0.70$) than frontal ($\omega^2 = 0.39$) sites. An additional Item Type $\times$ AP $\times$ SP interaction was found for Test 4 [$F(4,68) = 3.42$, $p < 0.05$, $\epsilon = 0.49$] reflecting the fact that, while this effect was reliable at most sites, it was only marginally significant at left frontal sites (f1: [$F(1,17) = 3.59$, $p < 0.08$]; f3: [$F(1,17) = 3.88$, $p < 0.07$]).

These results show that frontal and later parietal EM effects were indeed obtained in all 4 tests. Old-new effects¹ were also obtained at parietal sites during the 300–500 ms latency region in all tests. In fact, as depicted in Figure 3, the anterior distribution typical of the frontal EM effect during this early latency region was apparent for Test 1 only and, by Test 4, the distribution of this positivity had shifted to a parietal maximum. This suggests that test repetition may have modulated the magnitude of old-new effects over frontal and parietal sites differentially during the 300–500 ms latency region, with the changes in scalp distribution across tests reflecting either a decrease and/or increase of effects over frontal and parietal sites, respectively.

Comparison of effects between tests

300–500 ms latency region—ANOVA of the magnitude of old-new effects between tests revealed a Test by AP interaction [$F(3,51) = 7.39$, $p < 0.01$, $\epsilon = 0.93$]. Follow-up one-way ANOVAs failed to show a significant effect of Test over frontal sites [$F < 1$]. The same analysis over parietal sites revealed a main effect of Test [$F(3,51) = 6.22$, $p < 0.01$, $\epsilon = 0.93$], reflecting a linear increase in the magnitude of the old-new effects over parietal sites with each test repetition [$F(1,17) = 16.36$, $p < 0.01$]. Figure 4 illustrates this increased activity along with increasing memory discrimination accuracy (Pr) and the relative stability of the magnitude of the frontal EM effect across the four tests.

500–700 ms latency region—The ANOVA gave rise to a Test by AP interaction [$F(3,51) = 3.03$, $p < 0.05$, $\epsilon = 0.85$]. Follow-up one-way ANOVAs revealed a main effect of Test over frontal sites [$F(3,51) = 6.22$, $p < 0.01$, $\epsilon = 0.93$], but failed to show a significant effect of Test over parietal sites [$F < 3$]. The main effect of Test over frontal sites reflects an initial increase in activity over the first three tests, followed by a sharp decrease in activity in Test 4 as revealed by a significant quadratic trend [$F(1,17) = 7.30$, $p < 0.05$].

These findings suggest that there may be changes in the old-new scalp distribution across the four tests due to an increase in the magnitude of old-new activity over: (i) parietal, but not frontal, sites between 300–500 ms; and (ii) frontal, but not parietal, sites between 500–700 ms.

Topographic analyses

In order to explore the possibility that changes in old-new scalp distributions occurring across tests in each latency region reflect qualitative changes in the spatial configuration of the underlying neural generators (Urbach & Kutas, 2002) rather than simply quantitative changes

¹The term, ‘old-new effect’, will be used to denote differences between ERPs to old and new items, where old item ERPs are relatively more positive-going, to distinguish them from the early frontal (300–500 ms) and later parietal (500–700 ms) EM effects that have been previously associated, respectively, with familiarity- and recollection-based recognition.

in overall amplitude, we conducted topographic analyses on mean difference data (old-new). The data from all 60 electrode sites were rescaled using the range-normalization method (McCarthy & Wood, 1985). As we also wanted to evaluate whether the topography of these EM effects differed between the 300–500 ms and 500–700 ms latency regions in each test, the initial ANOVA employed the factors of Test (4), Latency Region (2) and Electrode Site (60). Any significant Test and/or Latency Region by Electrode Site interactions were followed up with subsidiary analyses to contrast the topography of EM effects for each latency region according to Test and/or for each test according to Latency Region. The initial ANOVA gave rise to interactions between Latency Region and Electrode Site [$F(59,1003) = 8.93$, $p < 0.001$, $\epsilon = 0.06$] and Latency Region, Test and Electrode Site [$F(177,3009) = 3.32$, $p < 0.01$, $\epsilon = 0.04$]. Follow-up subsidiary ANOVAs conducted separately within each latency region revealed a significant Electrode Site by Test interaction for the 300–500 ms latency region only [$F(177,3009) = 2.94$, $p < 0.01$, $\epsilon = 0.04$], reflecting the change in scalp distribution from a frontal maximum in Test 1 to a parietal maximum in Test 4 (see Figure 3). Subsidiary analyses conducted to contrast the topography of EM effects over the two latency regions for each test revealed significant Latency Region $\times$ Electrode Site interactions for Test 1 [$F(59,1003) = 9.21$, $p < 0.001$, $\epsilon = 0.06$], Test 2 [$F(59,1003) = 5.73$, $p < 0.001$, $\epsilon = 0.08$] and Test 3 [$F(59,1003) = 2.80$, $p < 0.05$, $\epsilon = 0.06$], but not for Test 4 [$p > 0.06$].

These findings indicate that, for the 300–500 ms latency region, with each subsequent test repetition, old item recognition increasingly engaged a different set, or at least differences in the relative strengths of the same set, of neural generators. The magnitude analyses revealed that these topographic differences are a result of increased old-new activity over parietal sites. The additional findings of significant topographic differences between the 300–500 and 500–700 ms latency regions in the first three tests, but not in Test 4, suggest that the parietal EM effect may be occurring at an increasingly early latency with each test repetition such that, by Test 4, it may be temporally overlapping the frontal EM effect.

Parietal EM effect – onset latencies

The onset latency of the parietal EM effect was investigated by segmenting the old-new difference measures from the 4 tests into 20 ms bins between 0–700 ms post-stimulus and then conducting t-tests in order to determine whether the averaged voltage within each bin was greater than zero. In order to control for signal to noise ratio across tests, we first recreated old and new item averages by sampling subsets of trials for each participant to equate the number of old and new item trials employed in each test (see Table 1B). Onset latency was defined as the time point at the beginning of the first of six consecutive time bins for which the amplitude was significantly greater than zero. These analyses were conducted on data collapsed over the 5 parietal sites used in the previous magnitude analyses. The results revealed that, with increased test repetitions, reliable parietal EM effects occurred at earlier latencies (test 1: 380–400 ms; test 2: 320–340 ms; test 3: 320–340 ms; test 4: 240–260 ms).

Together, the behavioral and ERP results indicate that, across test repetitions, as old-new discrimination improved and responses to correctly identified old and new items became increasingly faster, the magnitude of the parietal EM effect increased and its onset latency decreased. The following section explores whether these results reflect increased and faster recollection of symbols with each test repetition.

Effects of test repetition on familiarity and recollection

Behavioral data—To determine whether access to contextual information had increased across tests, we calculated, for each test, proportions of old items that were associated with correct and incorrect source judgments, as well as proportions of old and new items that were given R and K responses. These data are presented in Table 3 along with old item RTs to the

initial old/new judgment classified according to subsequent source and R/K judgments. As some participants made very few or no K responses or source errors in Tests 3 and 4, RT analyses were performed on the weighted means of the RTs across the four tests. Source and R/K judgment analyses were conducted only on old item data.

Source judgments—Source accuracy data were analyzed with an initial ANOVA employing the factors of Test and Source Judgment (correct vs. incorrect). This revealed a main effect of Source Judgment [$F(1,17) = 203.28, p < 0.001$] indicating that there was an overall greater probability of correct than incorrect source judgments for old items. There was also a main effect of Test [$F(1,17) = 74.58, p < 0.001, \epsilon = 0.57$]. However, these main effects were qualified by an interaction of Source Judgment with Test [$F(3,51) = 98.05, p < 0.001$]. Follow-up one-way ANOVAs performed separately on the proportions of correct and incorrect source judgments revealed main effects of Test (correct source: [$F(3,51) = 122.80, p < 0.001, \epsilon = 0.56$]; incorrect source: [$F(3,51) = 10.07, p < 0.001$]). These findings reflect a linear increase in correct source judgments [$F(1,17) = 280.65, p < 0.001$] and a concomitant linear decrease in incorrect source judgments [$F(1,17) = 17.10, p < 0.01$] across the four tests. An additional quadratic trend for the proportion of old items given correct source judgments [$F(1,17) = 28.18, p < 0.001$] reflects the fact that this increase in correct source identification leveled off by Test 4. For the RT data, a paired t-test revealed faster responses to old items associated with correct than incorrect source judgments [$t(17) = 2.81, p < 0.05$].

R/K judgments—For the analysis of R/K performance, proportions of old items associated with R responses (see Table 3) were adjusted to take into account the proportions of false alarms associated with the same responses. Thus, differences between the proportions of old and new items associated with R responses were calculated as follows: adjusted $pR_{old} = pR_{old} - pR_{new}$; adjusted $pK_{old} = pK_{old} - pK_{new}$. Under the assumption that R and K responses depend upon independent processes (Yonelinas & Jacoby, 1995), an estimate of familiarity was computed by dividing the proportion of known old items by 1 minus the proportion of remembered old items, and adjusted by performing the same calculations on the proportions of false alarms associated with the same responses (i.e., $[pK_{old}/1 - pR_{old}] - [pK_{new}/1 - pR_{new}]$). An initial ANOVA employing the factors of R/K and Test gave rise to a main effect of Test [$F(3,51) = 35.79, p < 0.001, \epsilon = 0.65$], reflecting a linear increase in the proportions of both recollected and familiar old items with each test repetition [$F(1,17) = 54.13, p < 0.001$]. An additional quadratic component for the familiarity measure only [$F(1,17) = 10.84, p < 0.01$], reflects the fact that this increase in familiarity for old items across test levels off by Test 4. RTs to old items that were known versus remembered were analyzed with a paired t-test which revealed faster responses to R items [$F(17) = 4.99, p < 0.001$].

In summary, access to contextual information became increasingly available with each test repetition as determined by both subjective (R/K judgments) and objective (source discrimination) measures. RTs to recollected old items were faster than those to old items that were simply familiar.

ERP data—The results of the earlier ERP onset latency analyses suggested that the putative ERP correlate of recollection (the parietal EM effect) may be occurring at an earlier latency with each test repetition. However, differences between the ERPs elicited by old and new items at parietal sites between 300–500 ms have been interpreted by some authors as indices of implicit memory (e.g., Friedman, 2004; Rugg et al., 1998). Hence, a competing interpretation of the earlier ERP findings is that an ERP index of implicit memory increases in magnitude with test repetition. If this is correct, the effect of test repetition on parietal amplitudes should not only be evident for recollected items, but also for those that are simply familiar. Alternatively, if the early parietal old-new effect reflects recollection, it should be selectively associated with items for which contextual information was retrieved. To adjudicate between

these alternative interpretations, we segregated ERPs to correctly identified old items according to whether they were subsequently associated with R or K responses². Because of very low trial numbers for some participants in one or more of the Item Type (R, K) by Test (1–4) cells, analyses of test-repetition effects were conducted separately for R and K items from different (although partially overlapping) subgroups of participants (R group: $n=14$; K group: $n=13$)³. Furthermore, for both groups, data were collapsed across Tests 1 and 2 (Early Tests) and Tests 3 and 4 (Later Tests) in order to retain a reasonable signal to noise ratio for ERP averaging (see Tables 1C and 1D for the number and range of trials contributing to the averaged ERPs). For the 300–500 ms latency region only, analyses of within-test data, and comparisons of old-new subtraction data between Early and Later Tests were conducted.

Analyses of R and K effects within Tests

Early Tests—ANOVAs, employing the factors of Item Type (R or K, new), AP and SP, for the Early Tests revealed main effects of Item Type for both the R group [$F(1,13) = 29.32$, $p < 0.001$] and the K group [$F(1,12) = 17.96$, $p < 0.01$] indicating greater positivity for R and K items than for new items. For the R group only, a Test by AP interaction was also obtained [$F(1,13) = 10.42$, $p < 0.01$], indicating that, while differences between R and new items were significant over frontal [$F(1,13) = 37.29$, $p < 0.001$] and parietal [$F(1,13) = 14.89$, $p < 0.01$] sites (revealed by follow-up tests), they were largest over frontal sites.

Later Tests—Initial ANOVAs gave rise to main effects of Item Type for both the R group [$F(1,13) = 23.21$, $p < 0.001$] and the K group [$F(1,12) = 12.38$, $p < 0.01$] indicating greater positivity for R and K items than for new items. A Test by AP interaction was also obtained for the K group only [$F(1,12) = 7.39$, $p < 0.05$], indicating that, while differences between K and new items were significant over frontal [$F(1,12) = 8.35$, $p < 0.05$] and parietal [$F(1,12) = 15.11$, $p < 0.01$] sites (revealed by follow-up tests), they were largest over parietal sites.

Comparison of R and K effects between Early and Later Tests

Analyses of difference score data revealed Test by AP interactions for both R [$F(1,13) = 19.23$, $p < 0.001$] and K [$F(1,12) = 8.44$, $p < 0.05$] groups, reflecting, across tests, a decrease in the magnitude of frontal EM effects and a concomitant increase in the magnitude of old-new effects over parietal sites. A Test by AP by SP interaction was also found for the K group only [$F(1,12) = 8.44$, $p < 0.05$], indicating that the decrease in the magnitude of frontal EM effects for K items was maximal over the left mid-lateral frontal site. However, follow-up one-way ANOVAs conducted separately over frontal and parietal sites, indicated that the decrease in activity over frontal sites and the increase in activity over parietal sites across test repetitions was significant only for the R group (frontal sites: [$F(1,13) = 4.68$, $p = 0.05$]; parietal sites: [$F(1,13) = 6.16$, $p < 0.05$]) and not for the K group (frontal sites: [$F < 1.9$]; parietal sites [$F < 1$]).

²R and K trials were collapsed across correct and incorrect source judgments and an ERP analysis of the source judgment data to investigate ERP indices of recollection and familiarity was not conducted. This is because ERP correlates of familiarity derived from incorrect source judgments may have been contaminated by items that were recollected, despite the fact that information relevant to the source judgment (i.e., location information) was not retrieved. This is supported by responses to the debriefing questionnaire indicating that, of the 18 participants, while 3 remembered location information only, another 12 retrieved various other details, such as providing names for, and/or making semantic associations to, studied items, or their distinctive shape. Another 3 participants failed to report the retrieval of any specific contextual details.

³For these, and subsequent, subgroups of participants, analyses of the behavioral data showed exactly the same pattern of results as for those already reported. Thus, we are confident that these subgroups are representative of the group as a whole.

⁴. Figure 5 illustrates these converse effects of test repetition over frontal and parietal sites for the R group.

These results indicate that the increased old-new activity at parietal sites between 300–500 ms with test repetition was selectively associated with R items and, thus, processes underlying recollection. If this test-repetition effect had reflected increases in implicit memory processing, a significant increase in parietal old-new activity should have also been evident for items that were simply familiar (i.e., K items).

Parietal EM effect for R and K items – onset latencies

To determine if the increasingly early onset of the parietal old-new effect with test found in the earlier ERP onset analyses was specifically associated with recollection, we assessed the onset latencies of the parietal old-new effects separately for R and K items for the Early and Later Tests using the same methods described previously. Tables 1E and 1F indicate the number and range of trials contributing to averaged R, K and new ERPs for these analyses. The results revealed that, for R items, the parietal old-new effect occurred reliably at an earlier latency in the Later Tests (300–320 ms) than in the Early Tests (380–400 ms). For K items, the opposite was true in that the parietal old-new effect was found to onset reliably at a slightly later latency in the Later Tests (400–420 ms) than in the Early Tests (360–380 ms)⁵. These findings indicate that the old-new parietal effect, which is occurring at an earlier latency with test repetition, appears to reflect recollection rather than implicit memory processing.

Direct comparison of ERPs to R and K items

In order to compare directly the ERPs to R and K items, we collapsed these data across the four tests for a subset of 16 participants. Averages were created by sampling subsets of trials for each participant to equate the number of R and K items employed in each test (see Table 1G). Analyses of these data involved a comparison of old-new subtraction data for the 300–500 ms latency region only. Figure 6 shows the grand-averaged waveforms to R & K items along with the corresponding scalp distributions of the old-new effects for this latency region.

An ANOVA, employing the factors of Item Type (R, K), AP and SP, revealed an interaction between IT and AP [$F(1,15) = 6.43$, $p < 0.05$], reflecting a marginally larger frontal EM effect for R than K items [$F(1,15) = 3.40$, $p < 0.09$], and differences in the distribution of old-new effects for R and K items, which are maximal over frontal sites for R items, and maximal over parietal sites for K items. This apparent difference in the topography of R and K old-new effects was confirmed with a comparison of rescaled R and K old-new data which revealed an Item Type (R, K) by Electrode Site (60) interaction [$F(59,885) = 2.64$, $p < 0.05$, $\epsilon = 0.06$].

Bringing together the behavioral and ERP data, although indices of familiarity and recollection increased across tests, concomitant increases in the magnitude of the parietal EM effect and decreases in its onset latency were selectively associated with R items and, thus, processes underlying recollection. Alongside the finding of topographic differences between R and K

⁴For a smaller subgroup of 10 participants, we also made a direct comparison between R and K old-new effects across early and later tests for the 300–500 ms latency region using data taken from 5 left parietal electrode sites (P3, P5, P7, PO3, PO7). A 2 (test: early vs. later) x 2 (item: R-new vs. K-new) ANOVA revealed a test by item interaction [$F(1,9) = 36.91$, $p < 0.05$], reflecting parietal old-new effects that are greater in magnitude in the later tests than in the early tests for R items [$F(1,9) = 14.69$, $p < 0.01$] but not for K items [$F < 1$]. The interaction also reflects the fact that the parietal old-new effects are greater in magnitude for R items than for K items in the later tests [$F(1,9) = 5.09$, $p = 0.05$] but not in the early tests [$F < 1$].

⁵Onset latency analyses for R and K effects from the same subset of 10 participants were also conducted using data taken from 5 left parietal electrode sites (see footnote 4). These analyses revealed a very similar pattern of results as reported for the different subsets of participants in the main analysis: For R items, the onset of the parietal old-new effect occurred earlier in the Later (300–320 ms) than in the Early Tests (420–440 ms). For K items, the parietal effect onset at the same latency for the Early and Later Tests (400–420 ms).

old-new effects, these results support the notion that recollection- and familiarity-based processes are functionally and neurally distinct.

Effects of conceptual processing

Behavioral data—Although the symbol stimuli used in our experiment were determined to be initially unnamable, the debriefing questionnaire indicated that 15/18 participants spontaneously associated some of the symbols with familiar objects or words and/or named some of the symbols as a mnemonic tool. The results of the symbol naming task (see ‘Procedure’), however, allowed us to determine, for 17 out of 18 participants (this data was not collected for 1 participant), which of the 40 old symbols had reminded them of a familiar object and/or they had ‘named’ at any point during the experiment. In fact, a greater percentage of old items were reported to have seemed familiar and/or been named (59.3%; sd: 26.4) than unfamiliar and/or not named (40.7%; sd: 26.4). This difference did not reach significance [$t(16) = 1.45$]. Thus, we were able to segregate putatively conceptually processed symbols (henceforth referred to as ‘named’ items) from symbols that had reportedly not been conceptually processed (henceforth referred to as ‘unnamed’ items). Of the 17 participants from whom we had collected naming data, one further participant’s data were excluded from all following analyses because they had not identified any old items as unnamed.

Recognition memory performance for named and unnamed studied symbols across the 4 tests was assessed by analyzing proportions of correctly recognized named and unnamed items (see Table 4) with an initial ANOVA which employed the factors of Test (4) and Item Type (named, unnamed). A main effect of Test [$F(3,45) = 54.78, p < 0.001, \epsilon = 0.71$] reflected a linear increase in the proportions of correctly recognized named and unnamed old items across tests [$F(1,15) = 79.72, p < 0.001$]. An additional quadratic trend [$F(1,15) = 23.56, p < 0.001$] indicated that this increase was steeper across initial test repetitions (i.e., Tests 1 and 2) compared to later test repetitions (i.e., Tests 3 and 4). There was an overall greater proportion of named, compared to unnamed, old items that had been correctly recognized [$F(1,15) = 8.18, p < 0.05$]. A t-test performed on the weighted RT means collapsed across the four tests to correctly identified named and unnamed items revealed faster responses to named items [$t(15) = 3.94, p < 0.01$].

Measures of recollection for named and unnamed items across the four tests were also determined by calculating, for each test, proportions of these items that were remembered (see Table 4). These were compared with an ANOVA, which employed the factors of Test and Item Type. A main effect of Test [$F(1,15) = 55.56, p < 0.001, \epsilon = 0.94$] indicated a linear increase in the proportions of remembered named and unnamed items across the four tests [$F(1,15) = 151.45, p < 0.001$]. A main effect of Item Type [$F(1,15) = 55.56, p < 0.001$] reflected an overall greater proportion of named than unnamed items that had been remembered.

In sum, increases in the proportions of recognized and recollected named and unnamed items were found across tests. However, overall, there was a greater proportion of named than unnamed items that were both correctly recognized and recollected. Responses were also faster to named, relative to unnamed, items.

ERP data—In order to assess the potential impact of implicit conceptual priming on the magnitude of the frontal EM effect, the ERPs to correctly identified old items were segregated according to whether or not they had been named. If the frontal EM effect is related to conceptual priming, then the magnitude of this effect should be greater for named than for unnamed items. Subsets of trials were sampled for each participant to equate, in each test, the number of R and K trials contributing to the averaged ERPs for named and unnamed items. As there were very low trial numbers for some participants in one or more of the Item Type (named, unnamed) by Test (1–4) cells, ERPs to named and unnamed items were taken from a sub-group of 13 participants and collapsed across the four tests to optimize the signal to noise

ratios (see Table 1G). Analyses of these ERP data were conducted for the 300–500 ms latency region only. Figure 7 shows the grand-averaged waveforms to named and unnamed items along with the scalp distributions of the old-new effects.

ANOVAs employing the factors of Item Type (named or unnamed, new), AP and SP revealed main effects of Item Type for named [$F(1,12) = 38.35, p < 0.001$] and unnamed [$F(1,12) = 38.43, p < 0.001$] items, indicating overall greater positivity for named and unnamed items than new items. ANOVA of the old-new subtraction data (named-new vs. unnamed-new) revealed only a marginal effect of Item Type [$F(1,12) = 3.46, p < 0.09$], indicating that the overall magnitude of old-new effects was marginally greater for named, than for unnamed items. A separate analysis of named and unnamed subtraction data was conducted on data from frontal sites only. There were no significant differences in the magnitude of frontal EM effects associated with named and unnamed items [$F < 2.3$].

The main finding here is that frontal EM effects were elicited by named and unnamed items, and were not modulated according to the putative conceptual processing of old items. Thus, this result does not support the notion that the frontal EM effect reflects verbally-mediated conceptual priming.

Discussion

Familiarity, thought to be a fast-acting, automatic and acontextual quantitative assessment of memory strength, and recollection, thought to involve the relatively slow and controlled retrieval of contextual information, are considered to provide distinct bases for making a recognition judgment. This experiment used pre-experimentally unfamiliar symbols to investigate the effect of multiple study-test repetition on the engagement of these two types of recognition-related processes and their purported ERP correlates. Across tests, the magnitude of the parietal EM effect increased and its onset latency decreased – these test repetition effects were associated with recollection but not familiarity. The magnitude of the frontal EM effect did not increase in association with increases in the estimates of familiarity and was not modulated by the conceptual processing of symbols. The topography of old-new effects associated with familiarity and recollection were also found to differ, with recollection effects showing a maximal anterior distribution and familiarity effects showing a maximal posterior distribution. We discuss our results below with respect to previous findings and dual-process models of recognition memory.

Behavioral Data

With each test repetition, old/new discrimination accuracy (Pr) and response bias (Br) increased, and RTs to correctly identified old and new items decreased. Thus, as expected, given multiple study-test opportunities with the same old symbols, participants' ability to discriminate between old and new items improved and appeared to be less effortful across the four tests. With each subsequent test, estimates of familiarity increased and access to contextual information also became increasingly available as determined by both subjective (R/K judgment) and objective (source discrimination) measures. The finding of faster responses to old items that were recollected (R items) compared to those that were simply familiar (K items) may, at first, seem incompatible with the idea that processes of familiarity are fast-acting while those of recollection are relatively slow. However, RTs to old/new judgments for R and K items do not necessarily reflect the speed of processing leading to the acquisition of memorial information associated with recollection and familiarity, which may well occur earlier for familiarity (Yonelinas, 2002). Instead, they measure the decision-making processes that are based on these qualitatively different types of information. Our pattern of RT findings suggests that participants found it easier to make an old/new decision based on the quite specific and distinct information associated with recollection compared to the relatively impoverished

information associated with familiarity. This concurs with previous reports which have suggested that familiarity-based recognition decisions will require greater monitoring and/or evaluative processing compared to those based on recollection (Dewhurst & Conway, 1994; Henson, Rugg, Shallice, Josephs, & Dolan, 1999).

ERP Data

Frontal EM effect

Familiarity: Relative to new items, old items elicited an enhanced positivity over frontal sites during the 300–500 ms latency region in all four tests. Given its latency and maximal amplitude over frontal sites in Test 1, this effect appears to resemble the frontal EM effect proposed to reflect familiarity-based recognition (Curran, 2000; Tsivilis, Otten, & Rugg, 2001). However, the scalp distribution of the old-new differences during this early latency region (collapsed across the 4 tests) differed for R and K items in our experiment, in which frontal-maximum and parietal-maximum distributions were associated, respectively, with recollection and familiarity. The frontal EM effect was also found to be marginally larger in magnitude for recollected, compared to familiar, items.

While these findings are surprising, they resemble those of another recent ERP study using unfamiliar faces (MacKenzie & Donaldson, 2007). These investigators reported a frontal EM effect for recollected, but not familiar, items during 300–500 ms latency region. Frontal and posterior maxima distributions were also associated, respectively, with recollected and familiar items, although these differences in scalp distribution were reported for the later 500–700 ms latency region in the MacKenzie and Donaldson study, rather than for the earlier 300–500 ms latency region as found here. Also, we had expected the magnitude of the frontal EM effect to increase along with an increase in estimates of familiarity. Instead, these effects remained stable across the 4 tests. Furthermore, when frontal EM effects were analyzed separately for R and K items, they *decreased* from early to later tests for both item types and significantly so for R items. According to dual-process models that assume familiarity and recollection are independent processes, there is no *a priori* reason to believe that familiarity should decrease as recollection increases. If this is correct, these findings provide little support for the idea that the frontal EM effect directly reflects familiarity-based recognition.

Conceptual priming: Previous reports that repeated stimuli which have no pre-existing semantic associations fail to elicit the frontal EM effect has led to a plausible alternative suggestion that the frontal effect may, instead, reflect conceptual priming (Voss & Paller, 2006, 2007; Yovel & Paller, 2004). In terms of this latter perspective, it has been proposed that the semantic processing of an item during study may enhance this type of implicit memory processing at test leading to early differences between old and new item ERPs. In support of this idea, using ‘nonsense’ figures and individual measures of meaningfulness, Voss and Paller (2007) reported a larger frontal EM effect for figures given high, compared to low, meaningfulness ratings. In the present study, we obtained individual measures indicating whether or not an old symbol had been conceptually processed at any point during the experimental session (i.e., whether or not old symbols had at any point reminded participants of familiar objects or if they had named these symbols in some way). The findings reported here are quite different from those of Voss and Paller in that the 300–500 ms frontal EM effects for purportedly conceptually and non-conceptually processed symbols did not differ in magnitude. Thus, our own findings do not support the idea that the frontal EM effect indexes conceptual priming.

The question, therefore, arises as to why these findings are so different from those reported by Voss and Paller. One possible reason for the discrepancy is that the electrode sites from which the data were analyzed in Voss and Paller’s study to assess modulations of the frontal EM

effect differed from those used in the present experiment. We chose to analyze data from the frontal electrode sites (F3, F1, Fz, F2, F4) most often used to assess the frontal EM effect in previous studies in order to enable comparisons between our own and previous findings. In Voss and Paller's study, the analysis showing differences between ERPs to high- and low-meaningfulness items used data from more anterior electrode sites, including data from frontopolar sites. In fact, Voss and Paller also conducted the same analysis using data from frontal and central electrode sites (which they called their 'middle region') and found, as for our own study, no differences between ERPs to high- and low-meaningfulness items. Thus, it seems likely that the discrepancy between our own and Voss and Paller's findings simply reflects the assessment of different ERP effects in the two studies.

In sum, findings from the present study provide little support for either of two prominent proposals regarding the functional significance of the frontal EM effect: that this effect reflects familiarity or conceptual priming. It has previously been suggested that the frontal EM effect may represent processing occurring downstream from processes signaling familiarity (Tsivilis et al., 2001). However, the modulation of this effect due to test repetition in the present study appears to have occurred in relation to recollection rather than familiarity and, collapsed across the four tests, was also found to be marginally larger for recollected than familiar items. Given that the effect was greater for recollected items during the early, compared to the later, tests indicates, for the stimuli used in the present experiment, that this effect may reflect some type of control processing that is particularly necessary to support the retrieval of contextual information when the memory trace is relatively weak.

Parietal EM effect

Parietal EM effects were elicited during the 500–700 ms latency region by correctly identified old items in each test phase. Parietal old-new effects were also elicited by the same items during the 300–500 ms latency region and were found to increase in magnitude across the four tests along with recognition performance. Furthermore, while the topography of the early (300–500 ms) old-new differences (frontal-maximum distribution) differed from that of the later (500–700 ms) old-new differences (parietal-maximum distribution) in Tests 1–3, by Test 4, the topography of the early and later old-new differences were found not to differ (both with mid-parietal maxima). Thus, it appears that the parietal EM effect may have temporally overlapped the frontal EM effect by the last test repetition. This idea was supported by the results of the onset analyses which showed that the parietal old-new difference was reliably elicited at an earlier latency with each test repetition.

These findings suggest that the neural correlate of recollection occurred at an earlier latency with each test repetition. However, as differences between ERPs elicited by old and new items at parietal sites between 300–500 ms have been interpreted by some authors as indices of implicit memory (e.g., Friedman, 2004; Rugg et al., 1998), it was possible that this early parietal old-new effect was an ERP index of implicit memory, such as repetition priming, rather than recollection. But the test repetition effects over parietal sites were evident for R items, and not for K items, indicating that this parietal old-new effect did, in fact, reflect recollection-based processes and not implicit memory. These findings were based on the separate analyses of R and K items for different subsets of participants and did not involve a direct contrast between R and K old-new effects. However, as described in footnote 4 and footnote 5, we showed more compelling evidence with an identical pattern of results when a direct comparison of R and K old-new effects were performed for a smaller subset of participants with sufficient R and K trial numbers. Nevertheless, the fact that items that were only familiar (K items) also elicited old-new effects during the 300–500 ms latency region which were maximal over parietal sites, suggests that one aspect of the early parietal old-new effect may also index some form of implicit memory such as repetition priming. Unlike the parietal EM effect associated with

recollection, however, the parietal old-new effect that is perhaps associated with repetition priming was not modulated by test repetition.

There are alternative explanations for the finding of increasingly early parietal activity associated with recollection. One possibility is that, with test repetition, an increasingly heterogeneous set of contextual details was retrieved, and that some of these details were retrieved more quickly than others, leading to overall faster recollection. That memory for different types of information may revive at different times is consistent with the source-monitoring framework (Johnson, Hashtroudi, & Lindsay, 1993) and has received empirical support (Johnson, Kounios, & Reeder, 1994). Alternatively, a relatively homogenous set of contextual details may have been retrieved across the four test phases but, as the memory traces strengthened with repetition, there may have been increasingly rapid access to these same details.

Conclusions

Our findings provide little support for proposals that the frontal EM effect reflects either familiarity or conceptual priming. Instead, the results suggest that this effect may reflect some type of control processing that is particularly necessary to support the retrieval of contextual information when the memory trace is relatively weak. The selective effects of test repetition on the magnitude and latency of the parietal EM effect for R items concur with previous findings that at least one aspect of old-new activity over parietal sites reflects processes of recollection. This neural dissociation converged with the finding of old-new topographic differences between items given R and K judgments to support the dual-process view that the processes associated with familiarity and recollection are neurally distinct.

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Acknowledgements

The authors wish to thank Charles L. Brown III for computer programming and help in all technical matters. We also thank Rebecca Edelblum and Brenda Malcolm for their assistance in participant recruitment and data collection, as well as Doreen Nessler for fruitful discussions. This research was supported in part by grant HD14959 from the NICHD and the New York State Department of Mental Hygiene. Reprint requests should be sent to Marianne de Chastelaine, Center for the Neurobiology of Learning and Memory, Department of Neurobiology & Behavior, University of California, Irvine, USA, or via e-mail: mdechast@uci.edu

Study

Test

Figure 1.

Experimental design – a schematic overview of a study-test block which was repeated four times for each participant. Cues for R/K and source (left, right) decisions were given in random order and only for an old response (rem = remember).

Figure 2.

Grand average ERP waveforms elicited by correctly classified old and new items at 6 electrode sites for each test. The electrode locations (F3, Fz, F4, P3, Pz, P4) are indicated on the top view of the schematic head in the center of the figure. Arrows mark stimulus onset with time markers every 500 ms.

Figure 3.

Surface potential maps (110° projections) showing the brain activity during the 300–500 ms and 500–700 ms latency regions used in the analyses. These maps show the distribution of negative (shaded) and positive (unshaded) voltages of EM (old-new) effects in each test.

Figure 4. Magnitudes of the frontal and parietal EM effects plotted against memory discrimination accuracy (Pr) across the four tests. The ERP data were collapsed across the 5 frontal and 5 parietal sites used in the magnitude analyses.

Effects of Test Repetition on R Items (300-500 ms)

Figure 5.

The effects of test repetition on the magnitudes of frontal and parietal old-new effects during the 300–500 ms latency region for R items.

Figure 6.

Grand average ERP waveforms elicited by correctly classified remembered, known and new items at 6 electrode sites (F3, Fz, F4, P3, Pz, P4) and scalp distributions for remembered and known old-new subtractions for the 300–500 ms latency region.

Figure 7.

Grand average ERP waveforms elicited by correctly classified named, unnamed and new items at 6 electrode sites (F3, Fz, F4, P3, Pz, P4) and scalp distributions for named and unnamed old-new subtractions for the 300–500 ms latency region.

Table 1

Mean number (and range) of trials contributing to old and new ERPs for each set of analyses:

[A] Comparison of old and new ERPs within and across the 4 tests.		
[A]	Old vs. New	n=18
<i>Test 1</i>		
	Old	21 (14–34)
	New	25 (16–30)
<i>Test 2</i>		
	Old	30 (20–39)
	New	25 (13–30)
<i>Test 3</i>		
	Old	36 (28–40)
	New	26 (21–30)
<i>Test 4</i>		
	Old	37 (32–40)
	New	27 (21–29)
[B] Onset latency analysis of parietal EM effects (old-new) for each of the 4 tests.		
[B]	Onset latencies (Old-New)	n=18
<i>Tests 1–4</i>		
	Old	21 (14–34)
	New	23 (13–29)
[C] Comparison of remembered and new ERPs within and across early and later tests.		
[C]	Remember vs. New	n=14
<i>Early Tests</i>		
	Remember	31 (11–60)
	New	49 (29–59)
<i>Later Tests</i>		
	Remember	55 (15–75)
	New	53 (44–59)
[D] Comparison of known and new ERPs across early and later tests.		
[D]	Know vs. New	n=13
<i>Early Tests</i>		

[D] Comparison of known and new ERPs across early and later tests.

[D]	Know vs. New	n=13
<i>Later Tests</i>	Know	28 (12–43)
	New	51 (43–59)
	Know	31 (15–59)
	New	53 (47–59)

[E] Onset latency analysis of parietal EM effects (remember-new) for early and later tests.

[E]	Onset latencies (Remember-New)	n=14
<i>Early/Later Tests</i>	Old	31 (11–60)
	New	48 (29–59)

[F] Onset latency analysis of parietal EM effects (know-new) for early and later tests.

[F]	Onset latencies (Know-New)	n=13
<i>Early/Later Tests</i>	Old	23 (12–39)
	New	49 (43–59)

[G] Comparison of ERP effects for known vs. recollected items.

[G]	Remember vs. Know	n=16
<i>(Across Tests 1–4)</i>	Remember/Know	34 (13–47)
	New	105 (95–118)

[H] Comparison of ERP effects for named vs. unnamed items.

[H]	Named vs. Unnamed	n=13
<i>(Across Tests 1–4)</i>	Named/Unnamed	36 (15–61)
	New	103 (73–118)

Table 2
Probabilities of correct responses and associated RTs to old and new items, and measures of old-new discrimination, Pr, and response bias, Br, as a function of test ($\pm$ SD).

	TEST 1 Mean (SD)	TEST 2 Mean (SD)	TEST 3 Mean (SD)	TEST 4 Mean (SD)
<i>Accuracy</i>				
Old	.56 (.15)	.79 (.16)	.91 (.08)	.95 (.05)
New	.86 (.12)	.88 (.13)	.90 (.08)	.91 (.07)
Pr	.41 (.11)	.64 (.16)	.78 (.10)	.83 (.08)
Br	.26 (.19)	.42 (.28)	.51 (.25)	.60 (.21)
<i>RTs (ms)</i>				
Old	722 (97)	704 (144)	664 (130)	648 (145)
New	765 (136)	746 (99)	700 (97)	677 (109)

Table 3

Proportions of old items assigned to correct and incorrect source judgments and proportions of old and new items assigned to remember and know judgments as a function of test., and weighted RTs to old items associated with each judgment type. Standard deviations are given in parentheses.

	Source Correct	Source Incorrect	Remember Old	Know Old	Remember New	Know New
Test 1	.39 (.15)	.17 (.08)	.25 (.18)	.31 (.11)	.02 (.03)	.10 (.09)
Test 2	.66 (.18)	.13 (.05)	.42 (.28)	.37 (.17)	.02 (.03)	.10 (.11)
Test 3	.82 (.13)	.09 (.08)	.57 (.26)	.34 (.23)	.01 (.02)	.08 (.07)
Test 4	.87 (.11)	.08 (.08)	.68 (.27)	.27 (.25)	.03 (.04)	.04 (.05)
RT	672 (124)	725 (129)	652 (112)	717 (128)	— [*]	— [*]

^{*} Note: There were too few Remember and Know responses to new items to meaningfully include the associated weighted RTs.

Table 4

Proportions of named and unnamed items that were correctly recognized, remembered and known as a function of Test, and weighted RTs associated with correctly recognized named and unnamed items. Standard deviations are given in parentheses.

	TEST 1 Mean (SD)	TEST 2 Mean (SD)	TEST 3 Mean (SD)	TEST 4 Mean (SD)	RTs (ms)
<i>Accuracy</i>					
Named	.60 (.18)	.83 (.14)	.92 (.09)	.97 (.04)	672 (108)
Unnamed	.48 (.23)	.76 (.20)	.89 (.12)	.93 (.09)	712 (136)
<i>Remember</i>					
Named	.31 (.23)	.49 (.30)	.66 (.23)	.78 (.24)	-
Unnamed	.12 (.13)	.31 (.27)	.50 (.31)	.59 (.27)	-