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Research report

# ERP old/new effects at different retention intervals in recency discrimination tasks

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**Abstract**

Recognition memory studies have suggested that event-related brain potentials (ERPs) may tap into several different memory processes. In particular, two ERP components have been hypothesized as related to familiarity (FN400 old/new effect, 300–500 ms, anterior) and recollection processes (parietal old/new effect, 400–800 ms, posterior). The functional significance of the FN400 old/new effect is uncertain because similar old/new differences have been shown to disappear at moderately long retention intervals. The present study investigated the effects of retention interval (34 min, 39 min, or 1 day) on the FN400 and parietal old/new effects in two different recency discrimination tasks. The results suggest that the FN400 old/new effect can be maintained across 1-day retention intervals, so it may index brain processes capable of contributing to long-term memory.


*Theme I:* Neural basis of behavior
*Topic:* Cognition

*Keywords:* Event-related potential; ERP; Memory; Familiarity; Recollection; Time

## 1. Introduction

Event-related brain potentials (ERPs) recorded about 300 to 800 ms after the onset of a recognition memory test stimulus show reliable differences between old (studied) and new (not studied) conditions (reviewed by Refs. [20,31,40]). The work of several groups (reviewed in Refs. [20,31]) has promoted the idea that an early (300–500 ms), mid-frontal, negative ERP effect is related to familiarity (here called the "FN400 old/new effect", for frontal N400), and a later (400–800 ms), parietal, positive ERP effect is related to recollection (here called the "parietal old/new effect"). This view is inspired by dual-process theories positing that recognition memory is controlled by separate processes of familiarity and recollection [2,24,25,29,34,38,51]. The present experiment examined the effects of retention interval on these ERP-correlates of recognition memory.

One influential review of the literature questioned the functional relevance of the early (300–500 ms) old/new effects because they disappeared across moderately long retention intervals over which behavioral effects of memory are still robust [40]. For example, in an indirect memory test requiring subjects to detect nonwords interspersed among words, the early ERP old/new effect to words lasted less than 15 min between the first (new) and second (old) presentations [39]. In a recognition memory experiment with words, the early old/new effect was not significant when 45 min intervened between the study and test lists [41], yet behavioral discrimination between old and new items remained above chance. If early ERP old/new effects do not last as long as behavioral discrimination performance, it seems questionable that ERPs could reflect the activity of brain processes causally related to memory performance. From this perspective, it has been argued that the 300–500 ms old/new effects may reflect short-term memory processes contributing to semantic language comprehension [35].

More recent evidence has supported the idea that the early (300–500 ms) FN400 old/new effect is related to familiarity because of its sensitivity to study/test similarity. According to prominent models of recognition memory, familiarity is the product of a global matching process that

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represents the similarity between a test item and all studied information (e.g., Refs. [3,21,23,43]). Several studies have now shown that the FN400 discriminates between studied items and dissimilar new items, but not between studied items and similar lures [5,11,33]. If these early FN400 old/new effects are as short-lived as those previously described [39,40,41], then this ERP correlate of familiarity may be too fleeting to be meaningfully related to recognition memory performance. Thus, the present study examined the persistence of the FN400 old/new effect across retention intervals ranging from approximately 30 min to 1 day.

In addition to examining the effects of retention interval, the present experiment was designed to investigate the brain processes underlying memory for time. Late (800–1800 ms), frontal ERP results from this same experiment most pertinent to memory for time have been published elsewhere [8]. Friedman [17–19] has proposed that at least two distinct processes underlie people's ability to remember when a past event occurred. First, distance-based processes estimate the amount of time that has elapsed between the event and the present based on strength, vividness, or the amount remembered about an event. Distance-based judgments are most accurate when the temporal separation between two events is large relative to their temporal separation from the memory test [18]. Second, location-based processes reconstruct times by retrieving contextual information surrounding the event in question. Location-based judgments are most accurate when events are associated with contextual information that is strongly tied to a particular time. Thus, unlike distance-based processes, location-based judgments can discriminate the time of occurrence of events separated by very little time if the events are associated with sufficiently different contexts and the times of those contexts are known.

Each subject in the present experiment participated on two consecutive days (see Table 1). The subject studied a single list of pictures on day 1, studied two additional lists on day 2, and then completed two memory tests on day 2. The study context was manipulated such that it was the same for lists 1 and 2, but different for list 3. Each test required subjects to make a three-choice discrimination between new items, items studied at time 1, and items studied at time 2. In the "Context" test, time-1 items were taken from list 2 (day 2) and time-2 items were taken from list 3 (day 2). Because lists 2 and 3 occurred closely in time yet were associated with different contexts, we expected performance to rely heavily on location-based reconstruction of context. In the "Day" test, time-1 items were taken from list 1 (day 1) and time-2 items were taken from list 2 (day 2). Because lists 1 and 2 were separated by a long interval and study context was held constant, we expected distance-based processes to be effective. Results from a memory-strategy questionnaire (described below) were consistent with the use of distance-based processes in the day test and location-based processes in the context test. As predicted by the view that frontal memory mechanisms are specifically related to location-based memory processing, we previously reported that late (800–1800 ms), frontal, memory-related ERP effects were larger (more positive) in the context than day tests [8]. The present report focuses on retention interval influences on the FN400 and parietal old/new effects and the light they may shed on the nature of the distance-based processes.

Table 1
Conditions

| Study list | Day | Context | Retention interval |
|---|---|---|---|
| 1 | 1 | 1 | 1 day |
| 2 | 2 | 1 | 39 min |
| 3 | 2 | 2 | 34 min |

Retention intervals are an averaged across subjects.

## 2. Materials and methods

### 2.1. Participants

Forty right-handed students from Case Western Reserve University participated in two sessions on consecutive days for a total payment of US$25. Data from 18 subjects were discarded because they did not have sufficient numbers of correct trials in each condition.[1]

### 2.2. Stimuli, design, and procedure

Stimuli were 300 grayscale line drawings from a commercially available clipart database ("Art Explosion" by Nova Development, Calabasas, CA) or from Snodgrass and Vanderwart [44]. Pictures depicted a variety of objects, animals, people (e.g., football player, nurse, woman with baby carriage), and scenes. Pictures were approximately 3.2 cm wide × 3.2 cm high and subtended a visual angle of approximately 3.16°. Pictures were rotated through the six experimental conditions across subjects.

Each subject participated on two consecutive days that included three study lists and two test lists. All variables were manipulated within subjects. The design of the study conditions is summarized in Table 1. On day 1, subjects studied a single list of 50 pictures (study list 1). On day 2, subjects studied a list of 100 pictures (study list 2), followed immediately by a list of 50 pictures (study list 3). The study-list context (specified below) was the same for study lists 1 and 2, but different for list 3. The Geodesic Sensor Net was fitted to subjects after list 3. The mean time interval between

[1] Seven subjects had insufficient numbers of artifact-free trails because of low accuracy in one or more conditions, five blinked excessively, three moved excessively, two misunderstood the key assignments, and one was removed because of an amplifier malfunction. The accuracy of these excluded subjects (except for those who used the wrong keys) was significantly lower than the included subjects in only the two studied context conditions.

the end of each study list and the beginning of test list 1 is listed in the last column of Table 1.

Subjects named each picture aloud during its 5-s study-list presentation (1 s ISI). Subjects were informed that their memory for the pictures would be tested on the second day of the experiment. Study context was manipulated by varying both encoding task and aspects of the environment in which pictures were presented. In environmental context A, pictures were presented against a yellow background, on a 17″ monitor, in a small, dark room, while sitting on a barstool. In environmental context B, pictures were presented against a red background, on a 21″ monitor, in a large, well-lit room, while sitting in a desk chair. Both contexts were separate from the test context. Contexts A and B were counterbalanced across subjects, so that A was presented first (lists 1 and 2) for half the subjects and second (list 3) for the other half. In addition, to strengthen the availability of contextual cues, one of two encoding tasks was assigned to each environmental context (counterbalanced across environmental contexts). Each task required subjects to rate the pictures on a 4-point scale by pressing one of four keys. In the liking task subjects rated how much they liked the picture (strongly dislike, somewhat dislike, somewhat like, strongly like). In the frequency task, subjects rated how frequently they encountered the things or situations represented in the picture (very rarely, somewhat rarely, somewhat often, very often).

In the day test, subjects pressed one key for pictures presented on day 1 (list 1, 1-day retention interval), another key for pictures presented on day 2 (list 2, 39 min), and a third key for new pictures. To encourage strength-based processing, subjects were specifically instructed: "When you complete this test it will often be helpful to just use your intuitive feel for whether an item was seen today or yesterday". In the Context test, subjects pressed one key for pictures presented on the first list of day 2 (list 2, 39 min), another key for pictures presented on the second list of day 2 (list 3, 34 min), and a third key for new pictures. To encourage location-based processing, subjects were specifically instructed that it would be helpful to remember the context in which they studied the pictures. Response keys for studied pictures were assigned to the first two fingers of one hand, and the new response key was assigned to the first finger of the other hand (counterbalanced across subjects). Each test list contained 150 pictures (50 per condition). Test-list order was counterbalanced across subjects. A memory-strategies questionnaire was completed after each test list.

Test-trial timing was synchronized to the 15 ms screen refresh rate. Each test trial began with an open circle (3.2 cm diameter) for a variable duration (525–1005 ms). The circle was replaced by the test picture for 1995 ms, which in turn was replaced by a central question mark. The question mark remained on the screen until the participant pressed a response key. An open square (3.2 cm sides) appeared after the participant responded and remained visible throughout the 2-s interstimulus interval. Participants were instructed to respond as quickly as possible, to remain motionless, and to minimize eye blinks.

The memory-strategy questionnaires contained 10 statements describing possible strategies that subjects might have used for each test (Appendix A). Subjects rated each strategy on a 7-point scale ranging from "never used" to "used on every picture".

### 2.3. EEG/ERP methods

Scalp voltages were collected with a 128-channel Geodesic Sensor Net™ [49] connected to an AC-coupled, 128-channel, high-input impedance amplifier (200 MΩ, Net Amps™, Electrical Geodesics, Eugene, OR). Amplified analog voltages (0.1–100 Hz bandpass, −3 dB) were digitized at 250 Hz. Individual sensors were adjusted until impedances were less than 50 kΩ. The EEG was digitally low-pass filtered at 40 Hz. Trials were discarded from analyses if they contained incorrect responses, eye movements (EOG over 70 μV), or more than 20% of channels were bad (average amplitude over 100 μV or transit amplitude over 50 μV). At least 21 acceptable trials were retained for each subject in each condition. The mean number of trials in each of the context conditions was: 39 min = 33, 34 min = 30, new = 41. The mean number of trials in each of the day conditions was: 1 day = 33, 39 min = 34, new = 35. Individual bad channels were replaced on a trial-by-trial basis with a spherical spline algorithm [47]. Consistently bad channels for a given subject were replaced throughout that subject's entire dataset (bad channels per subject: median = 1, mode = 0, range = 0–6). EEG was measured with respect to a vertex reference (Cz), but an average-reference transformation was used to minimize the effects of reference-site activity and accurately estimate the scalp topography of the measured electrical fields [1,9,13,28,37,50]. Average-reference ERPs are computed for each channel as the voltage difference between that channel and the average of all channels. The average reference was corrected for the polar average reference effect [27]. ERPs were baseline-corrected with respect to a 100-ms prestimulus recording interval.

## 3. Results

### 3.1. Behavioral results

Three separate analyses were conduced for each dependent variable. First, condition effects (first list, second list, new) were examined for the context and day tests separately. Condition (first list, second list, new) × Test (context, day) ANOVAs were not conducted because the identity of the first and second lists differed between the test types, so interpretation would be ambiguous. Second, task × old/new interactions were examined by comparing pictures studied at the 39-min retention interval (the only

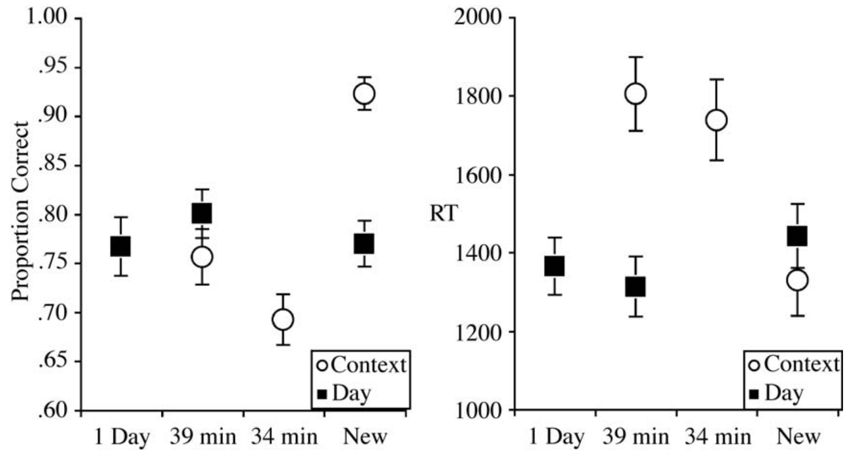


Fig. 1. Mean accuracy (left) and reaction time (right) in each condition. Error bars show the standard error of the mean.

study list represented in both tests) and new pictures for each test type.

Accuracy is shown in Fig. 1 (left). A repeated-measures ANOVA on the three conditions of the day test (1 day, 39 min, new) failed to identify any significant differences, $F(2, 21) < 1$, MSE = 0.01. Significant differences were observed among the context test conditions (39 min, 34 min, new), $F(2, 21) = 24.07$, MSE = 0.01, $p < 0.001$. Pairwise contrasts indicated that the two studied context conditions did not differ, but each significantly differed from new ($p < 0.001$). A task (context, day) × old/new ANOVA including only old items from the 39-min retention condition showed main effects of task and old/new that were qualified by an interaction between these factors, $F(1, 21) = 24.92$,

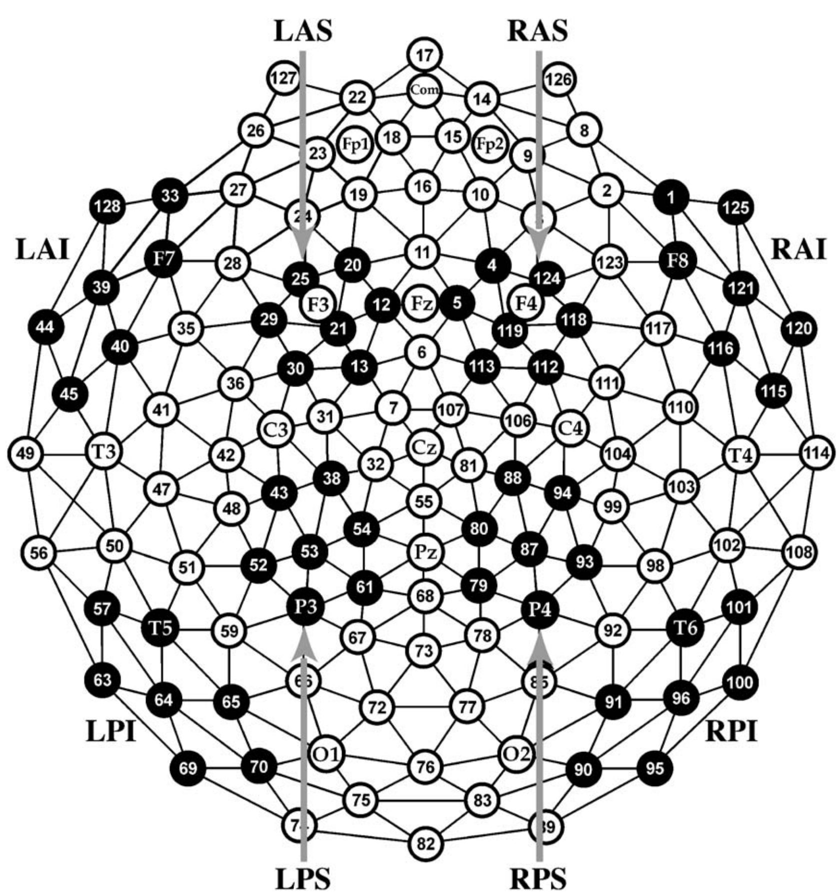


Fig. 2. Approximate sensor locations and selected locations from the 10–20 system. Channels within regions used in ANOVAs are shown in black. L = left, R = right, A = anterior, P = posterior, S = superior, I = inferior.

MSE = 0.01, $p < 0.001$. The interaction captured the fact that accuracy differed between tasks for new items, but not for old items.

Reaction times (RT) from accurate trials are shown in Fig. 1 (right). The three conditions of the day test (1 day, 39 min, new) differed only marginally, $F(2, 21) = 3.11$, MSE = 12711, $p = 0.06$. Significant differences were observed among the context test conditions (39 min, 34 min, new), $F(2, 21) = 34.08$, MSE = 38002, $p < 0.001$. Pairwise contrasts indicated that the two studied context conditions did not differ, but each significantly differed from new items ($p < 0.001$). A task (context, day) × old/new ANOVA including only old items from list 2 showed main effects of task and old/new that were qualified by an interaction between these factors, $F(1, 21) = 43.51$, MSE = 28650, $p < 0.001$. The interaction captured the fact that RT differed across tasks for old items, but not for new items. Overall, the finding that RT was slowest for old items in the context test is consistent with the idea that performance in the context task depends on the reconstruction of location-based information compared to the faster retrieval of distance-based information in the day task.

The memory-strategy questionnaire was employed to evaluate the use of strength versus context-based retrieval strategies. Strength-based strategies were probed with items 4, 7, and 9; context-based strategies were probed with items 2, 5, and 10 (other items were fillers). The strategies were analyzed by calculating each subject's mean rating across the strength and context items separately. Higher ratings indicate more prevalent use of each strategy. The results confirmed our prediction that distance-based strategies would be used more in the day test (MN rating = 4.91) than context test (4.14), $t(21) = 2.15$, $p < 0.05$; but location-based strategies would be used more in the context test (5.09) than the day test (4.45), $t(21) = 3.43$, $p < 0.01$.

### 3.2. ERP results

ERPs were analyzed with four separate methods described in the following sections: (1) Region of interest analyses, (2) 8-region analyses, (3) topographic analyses, and (4) principal components analysis (PCA). Each analysis focused on 300–500 ms FN400 and 500–700 ms parietal old/new effects. Later effects (800–1500 ms) from this experiment have been reported elsewhere [8]. ERPs recorded near selected locations from the international 10–20 system are shown in Appendix B, so the reader can see a wider sample of waveforms.

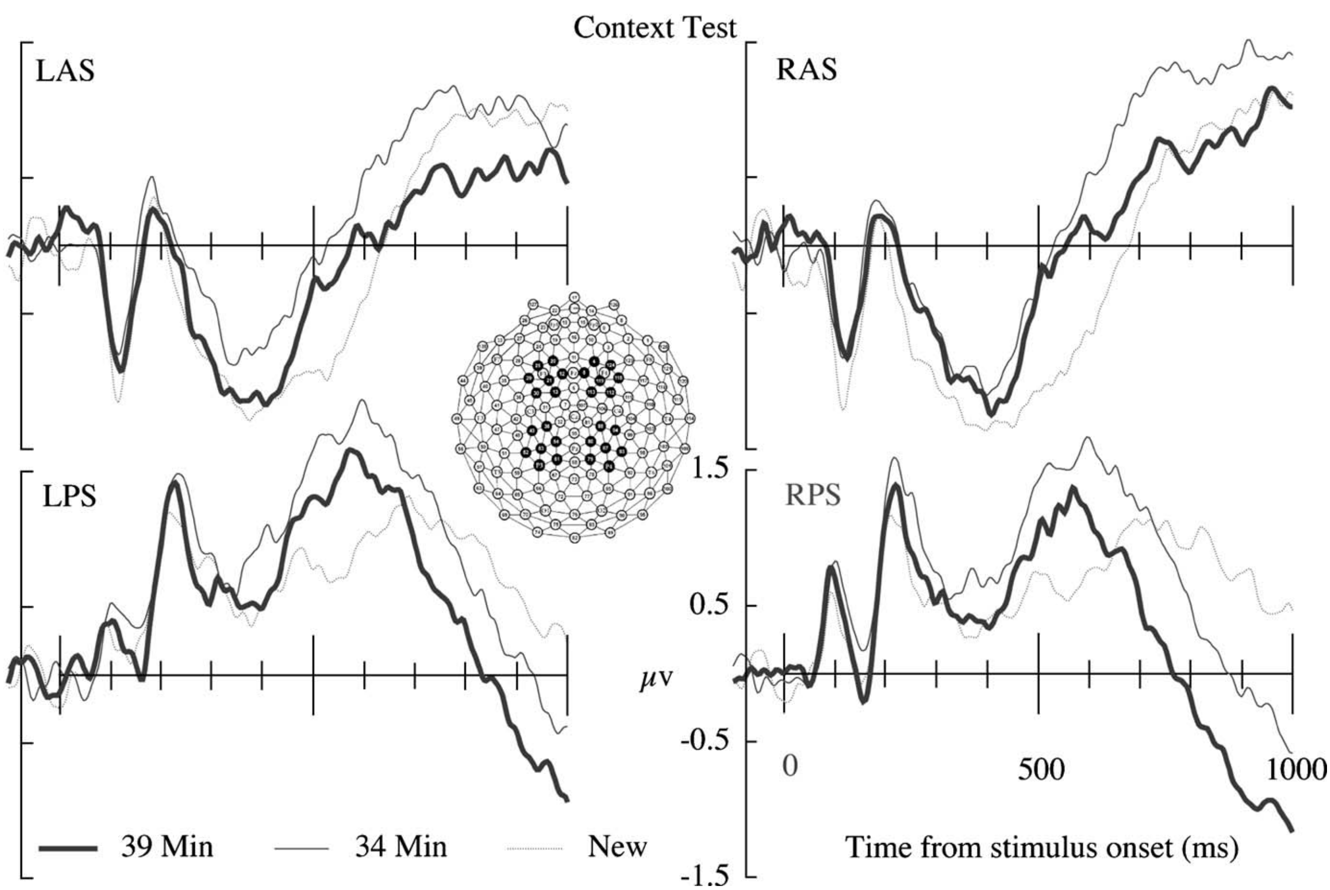


Fig. 3. Context test. Grand-average ERPs from ROIs used in ANOVAs. LAS is left/anterior/superior. RAS is right/anterior/superior. LPS is left/posterior/superior. RPS is right/posterior/superior.

### 3.2.1. Region of interest (ROI) analyses

FN400 and parietal old/new effects were analyzed within temporal windows (FN400: 300–500 ms; parietal: 400–800 ms) and spatial regions identified in previous studies (following Refs. [5–7,10,11]. These studies have found the FN400 old/new effect to be maximal between 300 and 500 ms near the F3 and F4 locations, whereas the parietal old/new effects are typically maximal between 400 and 800 ms near the P3 and P4 locations. Thus, ROIs were selected a priori, based on previous results. Fig. 2 shows the location of each region of interest (ROI). Fig. 3 (context test) and Fig. 4 (day test) show ERPs averaged within ROIs. For each component the dependent measure was mean voltage for each ROI. Mean amplitudes were computed by averaging across channels within each ROI. This procedure risks Type II errors when opposite-going effects at different channels within the ROI cancel each other, but visual inspection suggests that the results were not compromised in this respect, and this problem does not apply to the PCA. Separate condition × hemisphere repeated-measures ANOVAs were conducted to assess old/new effects at each retention interval and to directly compare results between retention intervals within each task. As in the behavioral results, analyses examining task × old/new interactions included only studied items from the 39-min retention interval. ANOVA results are summarized in Tables 2 and 3. Hemisphere × condition interactions are reported only when significant.

Table 2
FN400 ROI ANOVAs (300–500 ms, LAS and RAS Regions)

| Effect | *df* | *F* | MSE | *p* |
|---|---|---|---|---|
| *Context test* | | | | |
| 39 min vs. new | 1, 21 | 1.56 | 2.29 | n.s.[a] |
| 34 min vs. new | 1, 21 | 9.43 | 1.86 | < 0.01 |
| 39 min vs. 34 min | 1, 21 | 1.51 | 3.48 | n.s. |
| *Day test* | | | | |
| 1 day vs. new | 1, 21 | 15.67 | 1.54 | < 0.001 |
| × Hem | 1, 21 | 7.28 | 0.35 | < 0.05 |
| 39 min vs. new | 1, 21 | 4.91 | 3.92 | < 0.05 |
| 1 day vs. 39 min | 1, 21 | 0.09 | 3.15 | n.s. |
| *Test × old/new (39 min only)* | | | | |
| Test | 1, 21 | 0.20 | 3.78 | n.s. |
| Old/new | 1, 21 | 5.80 | 3.39 | < 0.05 |
| Test × old/new | 1, 21 | 1.11 | 2.82 | n.s. |

[a] Condition × inferior/superior interaction in 8-region analysis suggests that this effect is significant outside the ROI.

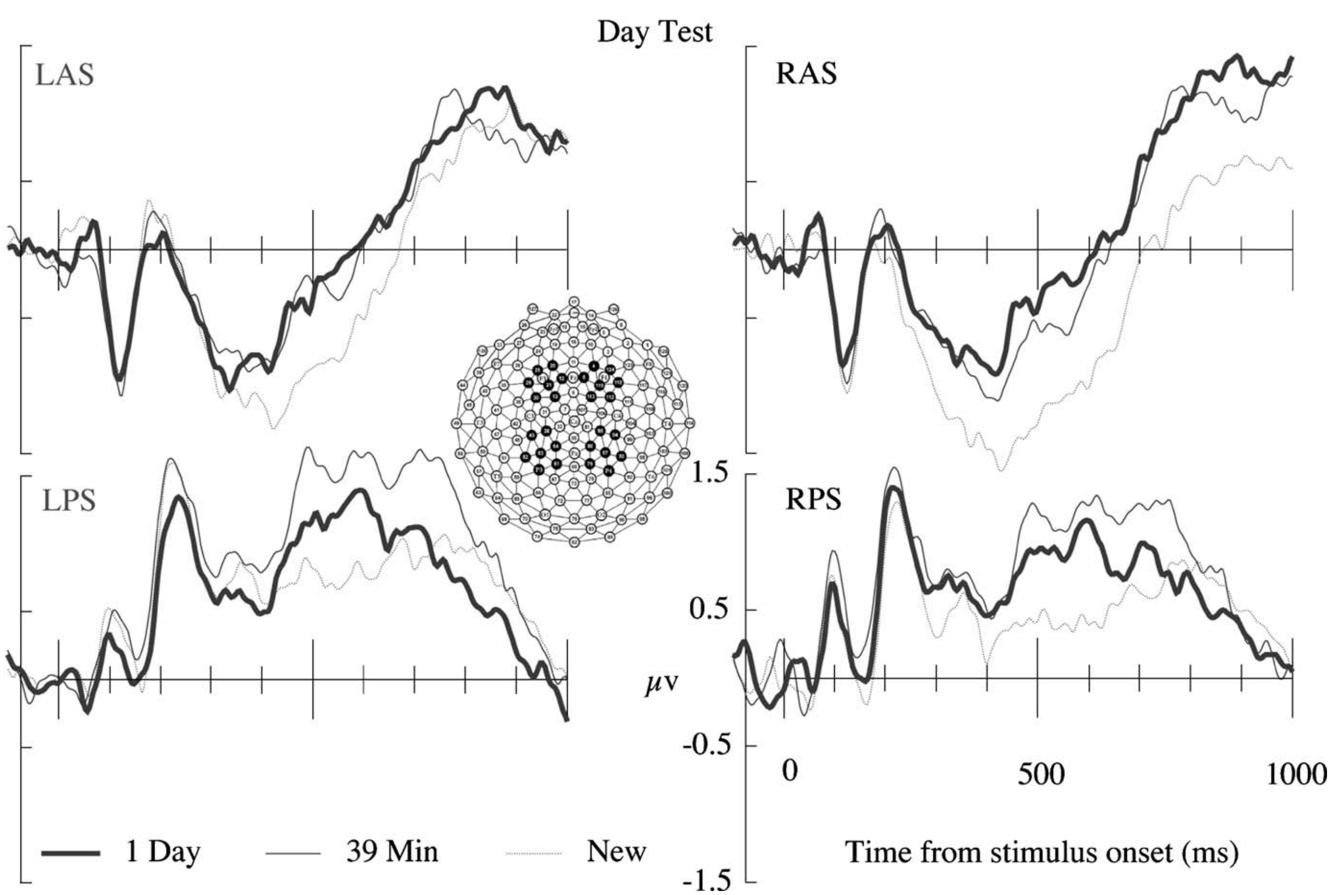


Fig. 4. Day test. Grand-average ERPs from ROIs used in ANOVAs. LAS is left/anterior/superior. RAS is right/anterior/superior. LPS is left/posterior/superior. RPS is right/posterior/superior.

Table 3
Parietal ROI ANOVAs (500–700 ms, LPS and RPS Regions)

| Effect | *df* | *F* | MSE | *p* |
|---|---|---|---|---|
| *Context test* | | | | |
| 39 min vs. new | 1, 21 | 3.08 | 3.53 | = 0.09[a] |
| 34 min vs. new | 1, 21 | 12.38 | 4.06 | < 0.01 |
| 39 min vs. 34 min | 1, 21 | 3.93 | 2.00 | = 0.06[a] |
| *Day test* | | | | |
| 1 day vs. new | 1, 21 | 4.03 | 3.88 | = 0.06[a] |
| 39 min vs. new | 1, 21 | 12.34 | 3.88 | < 0.01 |
| 1 day vs. 39 min | 1, 21 | 2.40 | 3.64 | n.s. |
| *Test × old/new (39 min only)* | | | | |
| Test | 1, 21 | 0.09 | 3.47 | n.s. |
| Old/new | 1, 21 | 11.48 | 4.54 | < 0.01 |
| Test × old/new | 1, 21 | 2.29 | 2.86 | n.s. |

[a] Condition × inferior/superior interaction in 8-region analysis suggests that this effect is significant outside the ROI.

The FN400 (300–500 ms) was analyzed over two anterior, superior channels groups (LAS and RAS regions in Fig. 2) centered near the standard F3 and F4 locations (following Refs. [5–7,10,11]). ANOVA results are shown in Table 2, and relevant mean amplitudes are shown in Fig. 5 (left). In the context test, FN400 old/new effects were observed at the 34-min retention interval, but not the 39-min retention interval. In the day test, FN400 old/new effects were significant at both the 1-day and 39-min retention intervals. A hemispheric interaction suggested that the difference between the new and 1-day conditions was larger over the right hemisphere, but the corresponding old/new effect was significant in each hemisphere alone ($p < 0.001$). Focusing on only studied pictures in the 39-min retention condition, the overall old/new effect was significant but did not interact with tasks.

The parietal effects (500–700) were analyzed over two posterior, superior channel groups (the LPS and RPS channel groups in Fig. 2) including the standard P3 and P4 locations (following Refs.[5–7,10,11]). We have often used broader temporal windows (e.g., 400–800 ms), but the 500–700 ms window was selected for several reasons. First, as examined later, spatial separation of the FN400 and parietal old/new effects was minimal in this experiment, so we chose to maintain temporal separation by starting the parietal window at 500 ms. Second, visual inspection suggested that the parietal old/new differences ended and later frontal effects began between 700 and 800 ms (described in Ref. [8]), so we chose to end the interval at 700 ms. Third, previous investigations have used the 500–700 ms window to analyze parietal old/new effects (e.g., Refs. [16,33]). ANOVA results are shown in Table 3, and relevant mean amplitudes are shown in Fig. 5 (right). In the context test, parietal old/new effects were significant after 34 min, but not after 39 min. Parietal amplitudes were marginally more positive for pictures tested after 34 min than after 39 min. For the day test, parietal old/new effects were significant after 39 min, but only marginally significant after 1 day. The direct comparison between the 1-day and 39-min conditions was not significant.

### 3.2.2. 8-Region analyses

ROIs were selected a priori based on previous results suggesting that FN400 old/new effects are maximal over superior, frontal regions, whereas parietal old/new effects are maximal over posterior, superior regions (following Refs. [5–7,10,11]). However, visual inspection of the topography of the present old/new differences (Fig. 6) suggests that this anterior/posterior separation was not clearly observed in the present experiment, so further

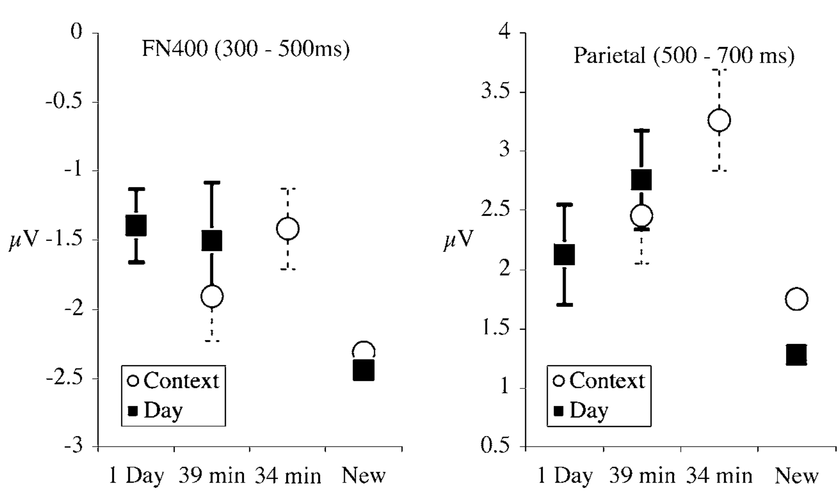


Fig. 5. Mean amplitudes (μV) corresponding to the FN400 (left) and Parietal (right) old/new effects. Error bars represent the standard error of the old/new difference (hence, the absence of error bars for the new conditions). Left: Mean amplitudes across the LAS and RAS regions from 300 to 500 ms. Right: Mean amplitudes within the LPS and RPS regions from 500 to 700 ms.

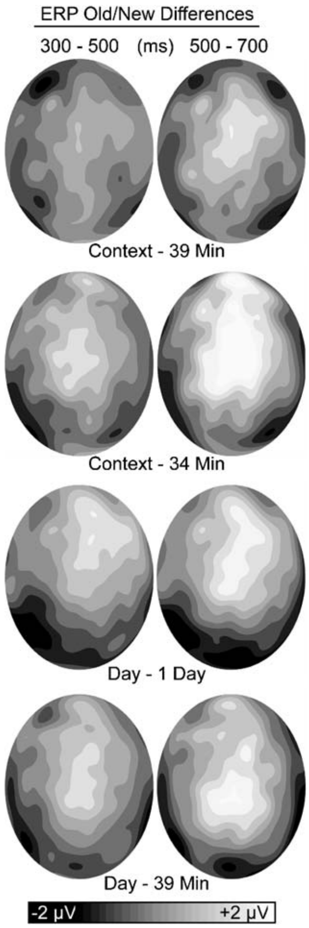


Fig. 6. Topography of the old/new differences estimated by spherical–spline interpolations [47]. The front of the head is depicted at the top of each oval. FN400 old/new differences are shown to the left (300–500 ms), and the parietal old/new differences are shown to the right (500–700 ms).

analyses included a broader distribution of electrode locations. Each of the ROI ANOVAs was redone in 8-region analyses with hemisphere × anterior/posterior × inferior/superior as spatial factors (see Fig. 2 for the locations of the eight regions). Previous research suggests that both the FN400 and parietal old/new effects, when observed with respect to the average reference, interact across the inferior/superior dimension such that old>new over superior regions, but new < old over inferior regions [4–6,11]. In keeping with this pattern, the primary result of the present analyses was that each of the condition main effects from the ROI analyses were associated with significant condition × inferior/superior interactions in the 8-region analyses. Rather than reporting the 8-region analyses in detail, we will only report results that clarify or modify the conclusions that would be drawn from the ROI analyses (see footnotes in Tables 2 and 3).

The ROI analyses suggest that anterior, superior FN400 (300–500 ms) old/new differences were significant in all but the 39-min context condition, and that retention interval did not significantly influence the magnitude of these effects. The 8-region analysis, on the other hand, resulted in a significant condition (39-min, new) × inferior/superior interaction, $F(1, 21) = 5.97$, MSE = 1.46, $p < 0.05$. As is typical for such old/new effects, superior amplitudes were more negative for new than old conditions, whereas inferior amplitudes were more positive for new than old conditions. Thus, all old/new differences within the FN400 temporal window were significant when a broader range of locations was considered. The ROI analyses suggest that posterior, superior parietal (500–700 ms) old/new differences were significant at the shorter retention interval within each test (context-34, and day-39), but were marginal at the longer intervals (context-39, and day-1). Furthermore, within the context test, differences between the two intervals were marginally significant. The 8-region analysis, on the other hand, showed significant old/new × inferior/superior interactions for each condition. In particular, considering those conditions with marginal old/new effects in the ROI analysis, these interactions were significant for the context-39 ($F(1, 21) = 17.28$, MSE = 2.34, $p < 0.001$) and day-1 conditions ($F(1, 21) = 40.98$, MSE = 1.30, $p < 0.001$). Furthermore, comparing the two retention conditions within the context test resulted in a significant condition × inferior/superior interaction, $F(1, 21) = 5.10$, MSE = 2.53, $p < 0.05$. In general, more effects were significant in the 8-region than ROI analyses because the parietal old/new effect was distributed more anteriorly than is typically observed. This observation begs the question of whether separate FN400 and parietal old/new effects were truly observed, so topographic analyses and PCA addressed the separability of these effects.

### 3.2.3. Topographic analyses

Old–new differences within each temporal window were computed within each of the eight spatial regions shown in Fig. 2 [4–6,11]. Amplitude differences between the conditions and temporal windows were removed by vector-length normalization, so that overall amplitude differences would not bias the topographic comparisons [30]. The normalized differences were the dependent measures in a condition × time (300–500, 500–700) × hemisphere × anterior/posterior × superior/inferior repeated measures ANOVA. Interactions between time and the topographic factors would indicate that the FN400 and parietal old/new effects are topographically different. As before, separate analyses focused on the context test, day test, and the task effects from the 39-min retention condition. In each of the following analyses, several lower-order interactions and main effects were significant, but only significant higher-order interactions most pertinent to interpretation are reported. Interpretation of several of these interactions can be facilitated by keeping in mind that both old/new effects typically interact across the inferior/superior dimension such that old/new differences are positive over superior regions, but negative over inferior regions, as can be seen in Fig. 6.

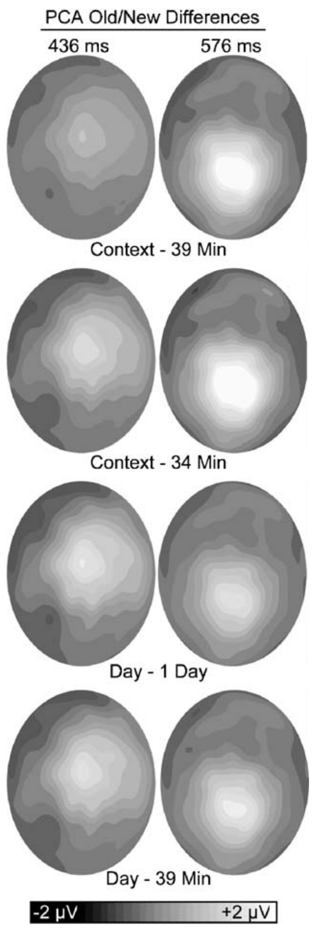


Fig. 7. The topography of the old/new differences for the two primary temporal-spatial PCA factors. The FN400 factor is to the left (436 ms), and the parietal factor is to the left (576 ms).

For the context test, normalized old/new differences were computed with respect to the 34- and 39-min retention conditions. Both of the following interactions were significant: time × hemisphere × anterior/posterior, $F(1, 21) = 5.56$, MSE = 0.03, $p < 0.05$; and time × hemisphere × inferior/superior, $F(1, 21) = 7.54$, MSE = 0.01, $p < 0.05$. The first interaction indicates that FN400 (300–500 ms) old/new differences were relatively larger than parietal (500–700 ms) old/new differences over left, anterior regions, but the opposite was true over left, posterior regions. The second interaction indicates that the superior/inferior differences over the right hemisphere are larger for the parietal (500–700 ms) than FN400 (300–500 ms) old/new effects. The condition × time × hemisphere × anterior/posterior × supesuperior/inferior interaction, $F(1, 21) = 5.28$, MSE = 0.01, $p < 0.05$, indicates that topographic differences between the FN400 and parietal windows within the 39-min condition were greatest over left, posterior, superior (parietal>FN400) and right, anterior, inferior (parietal < FN400) regions, whereas topographic differences within the 34-min condition were greatest over the right, posterior, inferior regions (parietal < FN400).

For the day test, normalized old/new differences were computed with respect to the 1-day and 39-min retention conditions. The time × hemisphere × anterior/posterior × superior/inferior interaction, $F(1, 21) = 5.27$, MSE =0.01, $p < 0.05$, indicates that the major topographic difference between the parietal (500–700 ms) and FN400 (300–500 ms) intervals is over left, posterior, superior (parietal>FN400) and right, anterior, inferior regions (parietal < FN400). The retention conditions were not associated with significant interactions.

The topographic analysis on task differences at the 39-min retention condition did not reveal any significant task interactions and was otherwise redundant with the previous topographic characterization of the old/new differences, so results of this analysis are not reported.

In summary, topographic interactions between the FN400 (300–500 ms) and parietal (500–700 ms) old/new differences indicated that the scalp distributions of these two effects are qualitatively different. In general, posterior, superior old/new differences were more prominent for the parietal than FN400 old/new differences.

### 3.2.4. Principal components analysis (PCA)

A temporal–spatial PCA was performed to better understand the spatiotemporal relationship among the ERP effects reported above [45,46]. A temporal PCA was followed by a spatial PCA—an approach that has previously been successful in characterizing the temporal–spatial covariance underlying the FN400 and parietal old/new effects [7]. The temporal PCA was calculated from − 96 to 900 ms with 17028 observations per time point (22 subjects × 6 conditions × 129 channels = 17028). Covariance was used as the measure of association. A Promax rotation [12,22] was used, which involves first applying a Varimax rotation and then relaxing it to allow for correlated factors. A scree test indicated that 18 factors should be retained (accounting for 82% of the variance). We focused exclusively on factors with time-courses similar to the FN400 and parietal old/new effects. An

Table 4
FN400 temporal–spatial PCA ANOVAs

| Effect | *df* | *F* | MSE | *p* |
|---|---|---|---|---|
| *Context test* | | | | |
| 39 min vs. new | 1, 21 | 2.24 | 3.25 | n.s. |
| 34 min vs. new | 1, 21 | 10.64 | 1.97 | < .01 |
| 39 min vs. 34 min | 1, 21 | 0.93 | 3.81 | n.s. |
| *Day test* | | | | |
| 1 day vs. new | 1, 21 | 35.37 | 0.81 | < 0.001 |
| 39 min vs. new | 1, 21 | 9.65 | 2.50 | < 0.01 |
| 1 day vs. 39 min | 1, 21 | 0.08 | 2.40 | n.s. |
| *Test × old/new (39 min only)* | | | | |
| Test | 1, 21 | 0.138 | 0.71 | n.s. |
| Old/new | 1, 21 | 8.90 | 3.25 | < .01 |
| Test × old/new | 1, 21 | 0.98 | 2.50 | n.s. |

Table 5
Parietal temporal–spatial PCA ANOVAs

| Effect | *df* | *F* | MSE | *p* |
|---|---|---|---|---|
| *Context test* | | | | |
| 39 min vs. new | 1, 21 | 20.60 | 2.65 | < 0.001 |
| 34 min vs. new | 1, 21 | 16.73 | 4.04 | < 0.001 |
| 39 min vs. 34 min | 1, 21 | 0.24 | 2.92 | n.s. |
| *Day test* | | | | |
| 1 day vs. new | 1, 21 | 12.42 | 1.94 | < 0.01 |
| 39 min vs. new | 1, 21 | 16.02 | 1.94 | < 0.001 |
| 1 day vs. 39 min | 1, 21 | 0.20 | 2.16 | n.s. |
| *Test × old/new (39 min only)* | | | | |
| Test | 1, 21 | 5.29 | 2.65 | < 0.05 |
| Old/new | 1, 21 | 26.03 | 3.22 | < 0.001 |
| Test × old/new | 1, 21 | 1.22 | 1.36 | n.s. |

"FN400 temporal factor" peaked at 436 ms and accounted for 44% of the variance. A "parietal temporal factor" peaked at 576 ms and accounted for 37% of the variance. The only other factor accounting for as much variability (44%) peaked at 876 ms, and corresponded to a commonly observed temporal factor peaking near the end of the epoch (e.g., Refs. [14,46]).

Separate spatial PCAs were performed on each of the temporal factors to identify separate sources of spatial variability within those temporal factors. Each data matrix consisted of 129 channels by 132 observations (22 subjects × 6 conditions = 132). Five spatial factors were retained for each temporal factor. For each temporal factor, a single spatial factor was identified that seemed related to the FN400 or parietal effects, based on visual inspection of the topography and condition effects. The topography of the old–new differences for each of these spatiotemporal factors is shown in Fig. 7. The spatial PCA procedure enforces identical scalp topographies for a given factor across all conditions, although they are free to differ in amplitude. The FN400 temporal–spatial factor (Fig. 7, left) peaked anterior to the parietal temporal–spatial factor (Fig. 7, right).

Factor scores were entered into ANOVAs that were analogous to those previously described for the ERP amplitudes. Table 4 shows results from the FN400 temporal–spatial factor, and Table 5 shows results from the parietal temporal–spatial factor. For the FN400 effects, the PCA results qualitatively match those of the ROI analysis—old/new effects were significant for all but the 39-min context condition. For the parietal effects, the PCA results were more like those of the 8-regional analysis, with significant old/new differences in each condition.

In summary, temporal–spatial PCA identified two patterns of covariance that are very similar to the FN400 and parietal old/new effects characterized in the conventional analyses with mean amplitudes. As in the topographic analyses, PCA results are consistent with the perspective that the two old/new effects are temporally and spatially distinct.

### *3.2.5. Summary of ERP results*

The 300–500 FN400 old/new difference was significant in every analysis for every condition except for the 39-min context condition. The ROI analysis and PCA both failed to observe significant old/new differences in the 39-min context condition, but the 8-region analysis did reveal a significant old/new × inferior/superior interaction, so there is some weak evidence for a FN400 old/new effect in this condition. None of the FN400 analyses revealed effects of test type or retention interval.

Both PCA and the 8-region analyses suggested that 500–700 ms parietal old/new effects were significant in every condition, but several of these differences were only marginal in the ROI analysis because the differences were distributed more frontally than is typically observed. Despite this frontal distribution, topographic analyses and spatiotemporal PCA confirmed that the parietal and FN400 old/new effects were distinct. The effects of retention interval in the context test and the test-type effects on 500–700 ms amplitudes were particularly mixed across the different analyses, so we do not consider them to be reliable.

## 4. Discussion

Despite previous evidence that 300–500 ms old/new effects are not significant at retention intervals as short as 15 or 45 min [39–41], we found the 300–500 ms FN400 old/new effect to be significant after 1 day.[2] Thus, the present results suggest that the FN400 old/new effect shows sufficient temporal persistence to be potentially relevant to behavioral memory phenomena, and they challenge any short-term-memory account of this ERP effect (e.g., Ref. [35]). Stimulus differences may contribute to the apparent inconsistency between the past and present results. Earlier studies showing that early old/new effects were fleeting used words as stimuli, whereas the present experiment demonstrating the persistence of these old/new effects used pictures as stimuli. Studies comparing forgetting rates between words and pictures have not yielded consistent results [36], but it is possible that forgetting was more extreme in previous ERP experiments with words than the present experiment with pictures. Rugg and Nagy's [41] old/new discrimination hit rate for words was 75% after 45 min, whereas our subjects' accuracy for pictures in the more difficult three-choice recency judgment task was 77% after 1 day.

[2] We acknowledge that the exclusion of 18 of 40 subjects may raise questions about the generality of these results. However, only seven of these subjects were rejected for reasons related to their memory ability, so we believe the present results are representative.

We previously reported that late (800–1800 ms) frontal ERPs in this same experiment were more positive during the context test than the day test, and that late frontal old/new differences were larger for the context than day tasks [8]. Together with behavioral results suggesting that reconstructive, location-based processes are more likely engaged by the context test, these late frontal effects may be related to such reconstructive processing. The earlier components reported here were not reliably modulated by either task or retention interval differences, so the present results do not clarify the manner in which the underlying memory processes contribute to recency judgments or are influenced by forgetting. We expected to observe FN400 and/or parietal differences related to distance-based processing between the 1-day and 39-min conditions of the day test, but no such differences were unambiguously observed. Given that processes underlying the FN400 and parietal old/new effects must at least be susceptible to forgetting, it seems likely that the present design was not sensitive enough to detect such differences. Accuracy was rescored to reflect old/new discrimination rather than recency judgments by scoring studied trials as correct whenever a non-new response was given (regardless of recency accuracy). From this perspective, both tests showed small, but significant retention interval effects. In the context test, hit rates were higher in the 34-min (MN = 0.95) than 39-min condition (MN = 0.92), $t(21) = 3.16$, SE = 0.01, $p < 0.01$. In the day test, hit rates were higher in the 39-min (MN = 0.95) than 1-day condition (MN = 0.91), $t(21) = 2.57$, SE = 0.02, $p < 0.05$. These retention effects are reliable, but probably not large enough to elicit corresponding ERP effects.

The only hint of an ERP retention interval effect was observed for the 500–700 ms parietal old/new effect comparing the 34- and 39-min intervals of the context test. The parietal effect was significantly larger for the 34- than 39-min condition in the region analysis, marginally significant in the ROI analyses, but non-significant in the PCA. It seems unlikely that this effect, if reliable, would be related to forgetting per se, because no such effect was observed after the longer, 1-day retention interval of the day test.

The present ERP effects were quantified with several different analyses, and the most critical FN400 old/new difference after a 1-day delay was significant in each analyses. Relative to an average reference, we have observed old>new differences over superior locations and old < new differences over inferior regions [5–7,10,11]. The superior and inferior regions typically provide redundant (i.e., approximately equal and opposite) information, so analyses can focus on superior ROIs. One advantage of the superior ROIs is that they are more comparable to results from other laboratories using the mastoid reference that maximizes superior old/new differences while minimizing inferior old/new differences. Thus, concentrating on superior regions, others have found FN400 old/new differences to be maximal over superior, frontal regions (near F3 and F4) and parietal old/new differences to be maximal over superior, posterior regions (near P3 and P4) [15,16,32,33,42,48]. In the present study, however, this frontal/parietal separation was not clear, so some old/new differences were statistically significant in only analyses that extended beyond the frontal and parietal ROIs. Such spatiotemporal overlap complicates component identification, but PCA proved helpful in this respect by segregating separate sources of variability that appear to be related to the 300–500 ms FN400 and 500–700 ms parietal old/new effects (see also Ref. [7]). The FN400-like factor peaked at 436 ms over regions that were somewhat more anterior than a later parietal-like factor that peaked at 576 ms.

In conclusion, the results from this experiment suggest that the 300–500 ms FN400 old/new effect can be maintained across 1-day retention intervals, so this ERP phenomenon may reflect the activity of brain processes capable of contributing to long-term memory.

## Acknowledgements

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## Appendix A. Memory-strategies questionnaire

1. Memory for the day of the week I saw a picture.
2. I judged when a picture had occurred by remembering what sort of judgment I had made about it.
3. I just guessed in which set a picture had been presented.
4. Clarity of my memory for a picture.
5. I remembered some of my thoughts about a picture when I studied it.
6. Whether a picture seemed to have occurred early or late among those pictures presented on a given day.
7. Vividness of my memory for a picture.
8. Memory for the approximate clock time when I saw a picture.
9. The strength of my memory for a picture.
10. I remembered the type of judgments I made for pictures that were studied nearby in the same list.

## Appendix B

Figs. A1 and A2

Please see the corrected version of Figure A1 that is appended to this file.

Fig. A1. Context test. Grand-average ERPs from channels representative of the international 10–20 system [26]. Channels are labeled according to Geodesic Electrode Net numbers (see Fig. 2) along with their nearest 10–20 equivalent location.

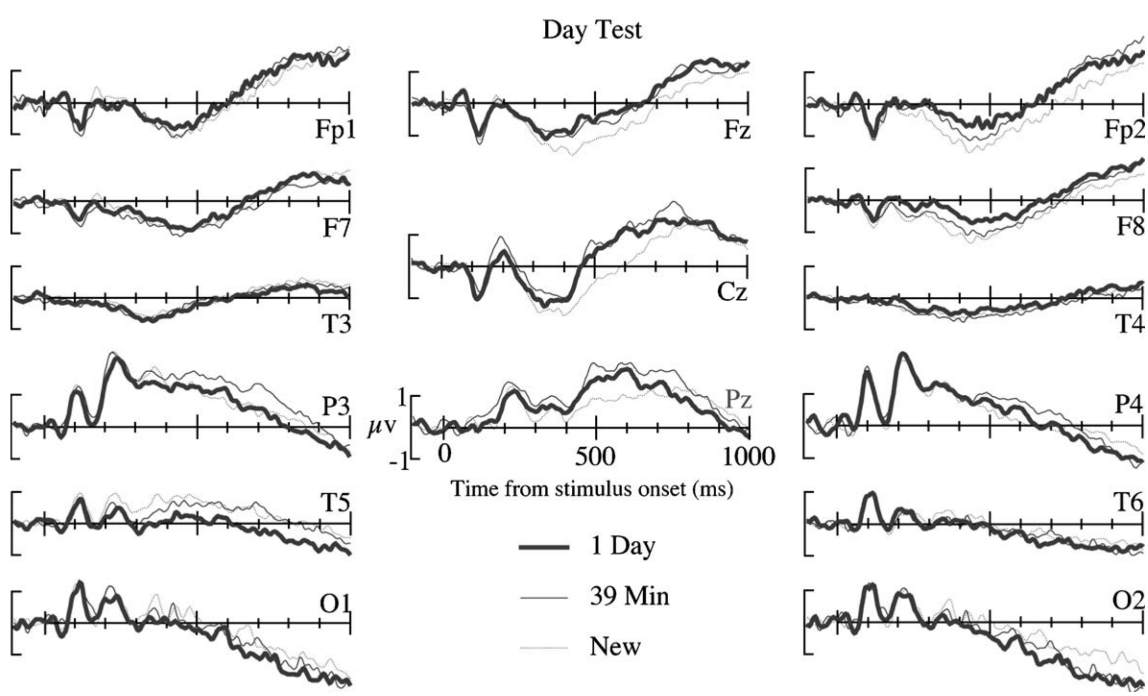


Fig. A2. Day test. Grand-average ERPs from channels representative of the international 10–20 system [26]. Channels are labeled according to Geodesic Electrode Net numbers (see Fig. 2) along with their nearest 10–20 equivalent location.

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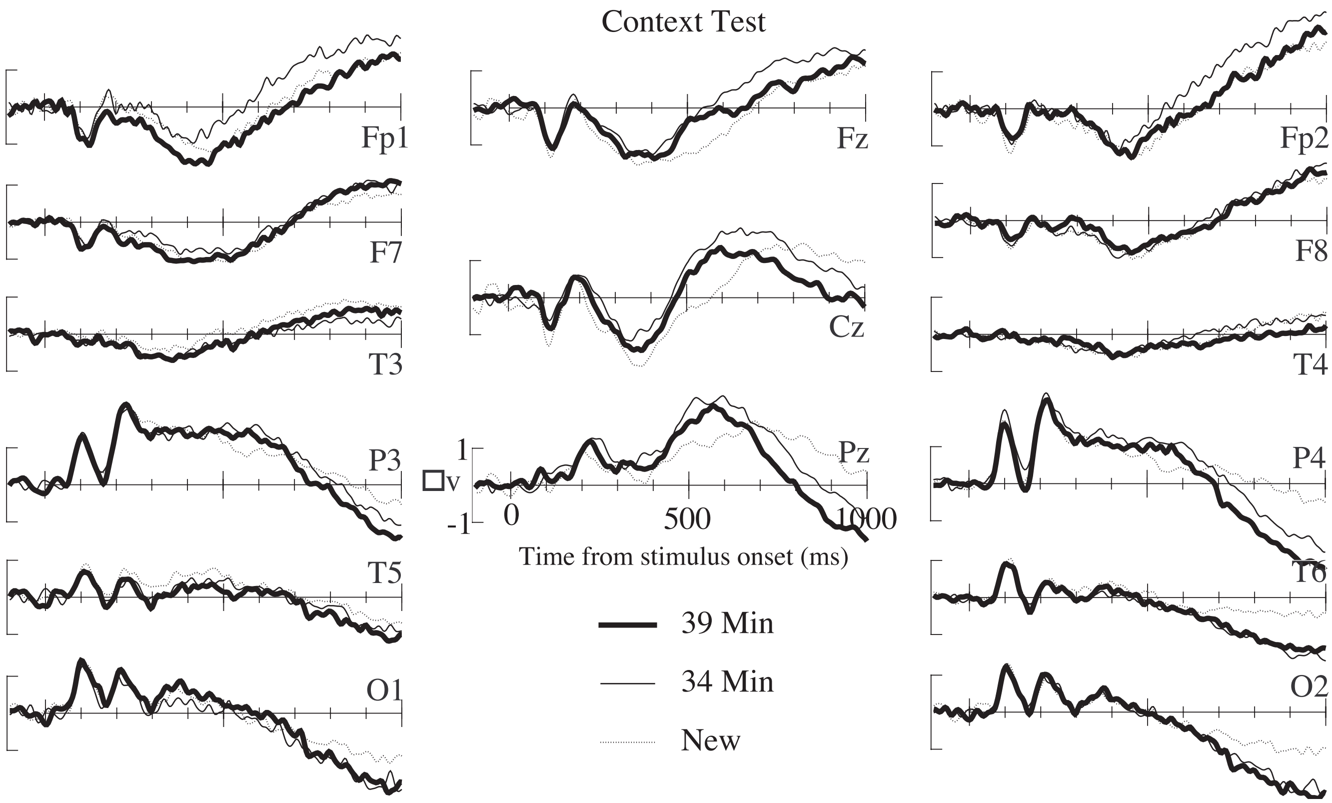
Corrected Version of Figure A1




* The originally published version of Figure A1 contains two errors:
1. Conditions are mislabeled.
2. Pz data is erroneously identical to the Pz data in Figure A2.

** Image appears clearer when printed or magnified with "zoom" in Acrobat.