

Research report

Attention and successful episodic encoding: an event-related potential study

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Abstract

Event-related potentials (ERPs) were used to delineate the cerebral processes occurring when information is encoded into episodic memory and to determine how these processes are affected by divided attention. ERPs were recorded during encoding under focused or divided attention, and were selectively averaged on the basis of their retrieval during later free recall and recognition tests (with remember–know judgments). Items retrieved with conscious recollection of the encoding episode (remembered, recalled) were distinguished at encoding from later missed items by an enhanced left fronto-temporal negative wave (N340), a negative posterior sustained potential and a positive frontal sustained potential. These effects occurred independently of the level of attention. Items later retrieved on the basis of familiarity (known) elicited a larger N340 than missed items, but did not demonstrate the increased sustained potentials. We suggest that item-specific conceptual processing (N340) is sufficient to produce familiarity-based recognition, but additional elaborative processing (sustained interaction of frontal and posterior regions) is necessary for conscious recollection. The effect of divided attention on these processes was related to the difficulty of the secondary task, with the more difficult task causing greater and earlier interference. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Attention is essential to the formation of a declarative memory trace. Reducing the attentional resources available for encoding information by distraction from a secondary task impairs performance on explicit tests of recall and recognition (e.g. Ref. [9]) but not on implicit tests such as word-fragment completion (e.g. Ref. [65]). In addition, when explicitly recognized items are categorized according to whether the retrieval experience is one of consciously ‘remembering’ the details of an encoding episode, or simply ‘knowing’ that it previously occurred [89], a secondary task at encoding specifically decreases the proportion of ‘remembered’ items (e.g. Ref. [28]). This

impairment may occur because the secondary task diverts time and attentional resources away from deep semantic processing. Support for this view comes from studies demonstrating that processing information at a physical or structural level rather than at a deeper, semantic level influences episodic memory performance in a manner similar to divided attention: free recall is impaired [11], and the proportion of items remembered during recognition is reduced [25,27,73]. Yet, the stage of processing at which the interference occurs may depend on the degree to which these resources are reduced. Moderate resource reductions may only interfere with relational and elaborative processing [8], whereas more severe reductions may affect basic semantic or even phonemic processing [54].

Moscovitch and Umiltà [53] proposed a model of memory and consciousness that describes how reduced resources might interfere with the cerebral processes responsible for episodic memory formation. They propose

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that the medial temporal lobe/hippocampal complex (MTL/H) only has access to information that has been consciously apprehended. The prefrontal cortex controls the extent to which incoming information is processed into consciousness through the mechanism of selective attention. When attention is divided across multiple tasks, fewer stimuli will reach the level of conscious awareness necessary for apprehension by the MTL/H. Furthermore, those stimuli that do reach this threshold may not be sufficiently encoded because the multitasking required by divided attention tasks occupies the supervisory capacities of the prefrontal cortex and interferes with the ability of this region to engage in the level of elaborative, semantic processing necessary for successful episodic encoding.

Many aspects of this model have been supported by blood flow studies in normal adults. Recent event-related fMRI studies of memory have shown maximal activation of frontal and parahippocampal cortices when items were subsequently recognized with either conscious recollection of the encoding episode (i.e. 'remembered') or with high confidence [3,93]. Items later recognized without either conscious recollection (i.e. 'known') or with low confidence did not differ from missed items. Furthermore, PET studies examining the effects of divided attention on episodic encoding have found that reduced resources affect activity in similar regions. Using a visuomotor secondary task and an auditory memory task, Fletcher and co-workers ([20]; see also Ref. [83]) found a specific decrease in left prefrontal activity (BA 46) at encoding as the demands of the secondary task increased. More recently, Idaka et al. [37] found that divided attention at encoding reduced blood flow to the left prefrontal and inferior temporal cortices, although it minimally affected the encoding-related activity of the left hippocampus. Taken together, these studies provide support for the view that divided attention interferes with the ability of the prefrontal cortex to carry out the semantic, elaborative processing necessary for successful episodic encoding.

Event-related potentials (ERPs), which measure neural activity that is time-locked to the processing of an individual stimulus, also have demonstrated differential neural activity associated with successful episodic encoding. Specifically, words later retrieved on a subsequent test of explicit memory typically elicit more positive-going potentials at encoding than words later forgotten (see Refs. [40,79] for review). Differences between the ERPs for words later recalled and those not recalled have been termed 'differences based on later memory' or Dm effects [5,62,63]. Although Dm effects involve multiple separate components, the most prominent of these are a transient posterior positive wave in the latency range of 300–800 ms and a sustained frontal positivity beginning at about the same time and lasting longer. These components are sensitive to different types of encoding instructions and therefore, may index different cognitive processes. For example, studies have shown that the transient posterior positive wave is more predictive of successful recall for

orthographically distinctive words that are studied under rote memorization instructions [17,18], whereas the sustained frontal positive wave is generally more predictive when words are studied under instructions that emphasize elaborative strategies such as semantic association, semantic verification or imagery [19,62,91,94]. These results suggest that the transient posterior positivity may represent item-specific evaluation and processing of distinctive information, whereas the sustained frontal positivity may represent inter-item associative encoding.

Although ERPs have not yet been used to examine episodic encoding in relation to attention, evidence suggests that both Dm effects index effortful processes that would be influenced by the demands of a secondary task. Fabiani and co-workers related the transient posterior positive wave to the P300 or P3b wave of the ERP, a centro-parietal positivity that follows the detection of task-relevant events [13,66]. The P3b is sensitive to attentional manipulation and indeed, may primarily index the amount of attention allocated to processing a stimulus [21,31]. For example, in a target detection task, the amplitude of the P3b is reduced in proportion to the degree to which attentional resources are diverted by a secondary task [96]. Some have argued, however, that the transient memory-related wave is not equivalent to the P3b because this Dm effect has a more widespread distribution [22,31] and is sensitive only to subsequent memory rather than to perceptual processing in general [62]. One way to reconcile these different interpretations is to consider the possibility that under certain circumstances, the amount of attention deployed in the processing of an item may predict subsequent memory for that item. Stimuli that are physically distinctive may elicit an orienting response that increases item-specific attention, and when elaborative strategies are not employed, this increase may be sufficient to influence and predict subsequent memory. However, elaborative strategies also require the sustained allocation of processing resources. Thus, it is also likely that attention is a necessary condition for the semantic, organizational processing associated with the sustained frontal positivity.

In the present study, we varied attention at encoding by having participants attend only to a series of visually-presented words (focused attention) or divide their attention between the words and an auditory-motor task (divided attention). As in neuroimaging studies of divided attention [37], we varied attentional demands by using easy and difficult versions of the secondary task. ERPs at encoding were averaged both as a function of subsequent memory performance and as a function of attention at encoding. These two averages provide somewhat different information about the encoding process. Averaging as a function of subsequent memory performance provides specific information about those encoding processes that are critical for successful storage in episodic memory. Averaging as a function of attention provides information about the general encoding mode, or neurocognitive set, during conditions of reduced attentional resources, as well

specific information about the stages of processing where reductions in attention influence encoding.

We categorized our ERP findings on subsequent memory performance derived from both free recall and remember–know recognition tests. We chose to use both types of test as the basis for selective averaging at encoding for three reasons. Firstly, in previous studies, Dm effects were generally largest and most reliable when based on free recall, smaller and less reliable when based on recognition, and essentially undetectable when based on implicit memory tests [45,55,61,64]. These findings suggest that Dm effects differentially index the conscious, controlled processes that predict successful episodic encoding. By this view, the weak relationship between Dm effects and recognition in these studies may have occurred because retrieval success on recognition tasks can arise from both conscious, controlled processes, which are associated with measurable Dm effects, and unconscious, automatic processes, which are not. This view also would predict, however, that robust Dm effects could be found when based on recognition performance if items retrieved on the basis of conscious recollection (R) and familiarity (K) were averaged separately at encoding.

It is therefore surprising that Smith [84] found no significant ERP differences at encoding between subsequently remembered items and subsequently known items, even though R and K responses could be dissociated at retrieval [14]. Investigators have disputed whether R and K responses index categorically different cognitive processes [29,39,76] or whether they simply differ in terms of trace strength (e.g. Refs. [12,36]), however all appear to agree that R responses involve the conscious recollection of the encoding context. Thus, if memory-related ERPs index processes related to episodic encoding, one would predict that they would differentiate items on the basis of subsequent R and K responses, either qualitatively — if they represent different cognitive processes, or quantitatively — if they exist as points along a unitary dimension. A more recent ERP study, however, found that younger adults showed greater sustained frontal positivity for subsequently remembered items than item subsequently known or missed [23]. Older adults did not show this differentiation, perhaps because of a failure to use elaborative encoding strategies, a deficit in attentional resources, or more lenient retrieval criteria. Thus, a second goal of the present study is to evaluate further whether R and K involve differentiable neural activity and whether ERP components associated with these responses are influenced by changes in attentional resources.

Finally, although successful recall and ‘remembering’ are both thought to arise from successful episodic retrieval [95], free recall and recognition tests have inherently different retrieval demands and are sensitive to different encoding processes. Whereas free recall benefits from relational processing that strengthens inter-item associations and facilitates strategic retrieval, recognition benefits more from item-specific processes that enhance the distinc-

tiveness and discriminability of the individual item [16,49]. With regard to R responses, some studies have emphasized their dependence on the type of elaborative, associative encoding that also benefits free recall [26]. Others have focused on the relationship of R responses to processing of salient or distinctive attributes of the individual item, which would largely benefit recognition [74]. The most parsimonious view is that both relational and distinctive item-specific processing contribute to the elaborative encoding that results in an R response. Therefore, in the present study, rather than give participants any specific encoding instructions that might result in preferential relational or item-specific processing, we simply encouraged participants to memorize the items. Yet, we averaged the encoding ERPs on the basis of whether the item was later recalled *and* remembered, remembered but *not* recalled, known, or missed. If posterior and frontal memory-related components index item-specific and relational processing, respectively, these components may be differentially sensitive to episodic encoding predictive of R items that can only be recognized, versus R items that can be both recalled and recognized.

In summary, we hypothesized that we would find a series of components in the ERPs recorded at encoding that would be sensitive to both the level of attention at study and the level of conscious recollection at retrieval. With regard to the effects of memory, we predicted that a posterior transient wave would be related to item-specific processing contingent on initial conscious apprehension of the incoming information, and that a sustained frontal wave would be related to subsequent elaborative processing. This prediction would be borne out by greater posterior positivity for both subsequently recalled *and/or* remembered items than missed items, but greater frontal positivity *only* for items that were both recalled *and* remembered. With regard to the effects of attention, we predicted attenuation of the sustained frontal positivity under dual-task relative to single-task conditions, regardless of the difficulty of the secondary task. We expected, however, that the more difficult secondary task would affect initial conscious apprehension of the item, and therefore would also attenuate the earlier transient posterior wave. Finally, because our recordings were more widespread over the scalp than in previous ERP studies of this type, an additional goal of this study was to explore other aspects of the encoding waveform that might be related to subsequent memory or attention.

2. Methods

2.1. Participants

Twenty young participants (mean age, 28 years; range, 22–37 years; nine female) were tested. All were right-handed, native English-speakers, with normal or corrected-to-normal vision and no history of neurological disorder.

All participants gave informed consent prior to the experiment. Data from three participants were lost due to corrupted data storage and data from two participants were discarded because of excessive skin potential artifacts. As a result, ERP averages were obtained from 15 participants.

2.2. Stimuli

The verbal stimuli for the memory task were 540 concrete nouns taken from the Kúcera and Francis [99] word-frequency norms. The words were 5–8 letters in length and had a mean word-frequency of 26 per million (range: 3–98 per million). From this word pool, six lists of 45 words were constructed for the study phase and six lists of these words plus 45 distractors were constructed for the test phase. The lists were equated for word-frequency. The words were displayed on a computer monitor in upper case yellow on a black background. On average, the stimuli subtended a horizontal visual angle of 2.0 degrees and a vertical angle of 0.7 degrees.

The stimuli for the auditory continuous performance task were low (250 Hz), medium (750 Hz) and high-pitched (2250 Hz) pure tones presented over speakers. The 750 Hz tone was presented at 55 dB sound pressure level (SPL). The other tones were adjusted to be equally loud.

2.3. Experimental procedure

Subjects were asked to memorize each list of 45 words for recall and recognition tests that would immediately follow the study list. They were given no specific instruction on how to memorize the words. Instructions for the recognition test included a description of the ‘remember’, ‘know’, and ‘new’ response categories, modeled on those used in previous studies [25,28,74]. The subjects were asked to respond ‘remember’ if the item brought back to mind specific associations, images or other personal experience that occurred when the word was first presented, to respond ‘know’ if they recognized that the word had been presented on the studied list but could not recollect the specific experience of studying the word, and to respond ‘new’ if they did not think that the item had been presented on the studied list. These instructions were reviewed before the start of each recognition test. At the end of the experiment, participants were debriefed about the strategies they used during the different encoding conditions.

During the study phase, participants viewed and attempted to memorize 45 words presented for 2000 ms each in a randomized sequence. Between words, participants fixated on a centrally presented crosshair (+) for 1500 ms. In the focused attention condition, participants performed the memory task alone. In the easy and difficult divided attention conditions, participants performed the memory task simultaneously with an auditory continuous performance task. The participants used the index, middle,

and ring fingers of their right hand to press the left, middle, or right button in response to the low, medium and high-pitched tones, respectively. The next tone began 200 ms after the participant pressed a button.

In the difficult divided attention condition, the tones were presented in a random order with the exception that a given tone would not immediately repeat. The participants were instructed to respond as quickly and accurately as possible and to divide their attention equally across the memory task and auditory task. In the easy divided attention condition, tones were presented in a repeating three-tone pattern (low, medium, high). In this condition, participants were asked to respond accurately, to pace their responses at a rate of about 1 response per second (to approximate the rate used for the difficult task), and to attend primarily to the memory task. The relatively slow pacing of responses in the easy divided attention condition was done to make the number of tones and responses roughly equal between the easy and difficult version of the task and to ensure further that the easy version placed minimal demands on attentional resources. Before and after the experiment, participants performed the difficult auditory task alone for 50 trials each. The average performance on these pre- and post-experimental tasks provided a baseline reaction time (RT).

At the end of each study list, participants counted backwards by 3 s from an arbitrarily chosen three-digit number for 1 min. Participants then performed a free recall test in which they were given 3 min to verbally recall as many items from the preceding study list as possible. Participants were then given a recognition test. In this test, first a central fixation point was displayed for 1000 ms, then a word was presented for 2000 ms, during which time the participant determined whether he or she recognized the word but did not overtly respond. At the end of the presentation interval, the word remained on the screen and a response cue (‘1=remember, 2=know, 3=new’) appeared beneath the word until a keyboard response was made with the right hand.

2.4. Electrophysiological recordings

EEG activity was recorded from the scalp using 46 tin electrodes. Thirty-six electrodes were embedded in an elastic cap at standard locations [2] as illustrated in Figs. 2 and 3. Additional electrodes were placed at F9/F10, TP9/TP10, Nz, and at the back of the neck. Cerebellar electrodes (Cb1/Cb2) were placed at 50% of the distance from Iz to TP9 and TP10. Eye movements and blinks were recorded with electrodes 1 cm lateral to the outer canthi (LO1/LO2) and over the infra-orbital ridge (IO1/IO2). Inter-electrode impedances were kept below 2 k Ω . All electrodes were referenced to Cz and subsequently converted to an average reference. All channels were recorded with a bandpass of 0.05–70 Hz, digitized at a rate of 250 Hz, and stored off-line for analysis.

Following artifact rejection to remove trials contaminated by muscle artifact ($\pm 600 \mu\text{V}$), ERP sweeps were selected from 100 ms before word onset to 3500 ms after word onset. EOG artifacts were compensated using ocular source components [69]. Ocular source components were derived from an initial calibration recording during which the participant blinked and made repeated saccadic eye movements in the vertical and horizontal directions. Between three and five components were selected to model the average eye movements, depending on how much variance each component contributed to the calibration recordings and how clearly they represented ocular movements. This correction procedure was carried out in BESA version 2.2, which required a reduction in waveform resolution from 4 ms to 20.9 ms.

During our recordings from the first 10 participants, small skin potential artifacts became apparent despite low inter-electrode impedances. The demands of the secondary task increased the size and incidence of these potentials. To reduce the prevalence of skin potentials in the subsequent 10 participants, the skin beneath electrodes over frontal and temporal regions was punctured with a fine-gauge, sterile needle to reduce the impedance to less than $1 \text{ k}\Omega$ [68]. Additionally, following recording, we rejected all individual trials in which recognizable skin potentials were present, resulting in an average reduction of 7% of trials per condition per participant (range: 0–39%). Data from two participants had to be excluded from further analysis since this procedure left too few trials for averaging.

2.5. Data analysis

2.5.1. Behavioral data

Performance during free recall was measured as the percent correctly recalled out of 45 items. For recognition, overall hits, false alarms (FA) and corrected recognition (hits – FA) were calculated for R and K. Additionally, if we assumed that R and K were independent [38], we could estimate the independent probability of R by dividing the incidence of R by $(1 - K)$ and the independent probability of K by dividing the incidence of K by $(1 - R)$. Both of these estimates were corrected for false alarms.

The mean RT on the secondary task was based only on correct responses. For both memory and RT measures, we averaged performance across the two study-test blocks for each of the three encoding conditions. All behavioral data were analyzed with repeated-measures ANOVAs and post-hoc *t*-tests with alpha levels of 0.05.

2.5.2. Electrophysiological data

For each of the three attention conditions (focused attention, easy divided attention, difficult divided attention), the ERPs at encoding were sorted into one of four categories on the basis of subsequent memory performance: (a) items subsequently recalled and assigned a ‘remember’ response on the subsequent recognition test

(RR), (b) items not recalled, but assigned a ‘remember’ response on the subsequent recognition test (‘remember only’ or RO), (c) items not recalled, but assigned a ‘know’ response on the subsequent recognition test (K), and (d) items neither recalled nor recognized (‘missed’ or M).

Individual participant waveforms were then created by averaging the ERP as a function of subsequent memory performance (collapsing across encoding condition), and by averaging as a function of encoding condition (collapsing across subsequent memory performance). Within an individual participant, the averaging was trial-weighted. When combining data across participants, each participant contributed equally to the grand mean waveforms. The mean trial counts going into the grand mean waveforms for focused, easy divided and difficult divided attention were 82.3 (range: 54–88), 82.5 (range: 59–88) and 79.1 (range: 56–88), respectively. The mean trial counts going into the grand mean waveforms for RR, RO, K and M conditions were 55.3 (range: 32–80), 53.3 (range: 14–90), 64.2 (range: 26–98) and 69.2 (range: 20–123), respectively.

Components identified from the grand mean waveform were evaluated using both peak and mean amplitude measurements. Two early waves were measured: a positivity peaking at 120 ms (P120) and a negativity peaking at 180 ms (N180), both of which were maximally recorded in the temporo-occipital regions. Within the 200–400 ms latency window, measurements were taken of a fronto-central positivity peaking at 200 ms (P200), a posterior positivity peaking at 280 ms (P280) and a fronto-temporal negativity peaking at ~ 340 ms (N340). A broader, posterior positivity peaking at ~ 550 ms (P550) was evaluated using mean amplitude measurements from the 400–800 ms latency window. Frontal and posterior sustained potentials were quantified in three successive 500 ms time windows from 500 to 2000 ms. Larger time windows were used because an initial analysis of the data indicated that there was little change in scalp topography of the sustained potentials within these intervals. All amplitudes were measured relative to the average amplitude over the 100 ms preceding stimulus-onset.

Amplitudes were statistically analyzed only at the electrode(s) where activity was maximally recorded and at the homologous electrode(s) in the contralateral hemisphere using repeated-measure ANOVAs with appropriate Greenhouse–Geisser corrections. Main effects and interactions significant at the $P < 0.05$ level were further analyzed using Tukey’s honestly significant difference.

To assess the relationship to subsequent memory, ERPs were averaged as a function of subsequent performance on the recall and recognition test and were analyzed using 4 (recalled/remembered, remembered only, known, missed) $\times 2$ (hemisphere) repeated-measures ANOVAs. To assess the effects of attention, ERPs averaged as a function of encoding condition were analyzed using 3 (focused, divided easy, divided difficult) $\times 2$ (hemisphere) repeated-measures ANOVAs.

Where possible, we also investigated the interactions between attention and memory. When the ERPs were separated on the basis of both attention and response at retrieval, the mean number of trials in each cell ranged from 7.0 (RO in difficult divided attention) to 45.4 (M in difficult divided attention). Because the number of trials in certain cells was quite small, we attempted to reduce noise and improve statistical power by first combining ERPs for items subsequently recalled and remembered (RR) with those for items subsequently remembered only (RO) to create a category of ‘remembered’ items (R). Secondly, to simplify the analyses, we made only two comparisons. Items later known were compared to items later missed (K versus M) to assess the activity necessary for subsequent recognition, and items later remembered were compared to items later known (R versus K) to assess activity necessary (in addition to the preceding effects) for recognition to be episodic in nature. Thirdly, in order for an effect in a given encoding condition to be included in this analysis, we required that there be a sufficient number of participants (>8) with a sufficient number of trials (>10) of that type. These criteria limited our analysis of R versus K to a comparison between focused and easy divided attention conditions, and our analysis of K versus M to a comparison between easy and difficult divided attention conditions. For the R versus K comparison, the mean trial counts for R waveforms were 45.7 (range: 27–62) for focused attention and 36.6 (range: 15–58) for easy divided attention. Mean trial counts for K waveforms in this comparison were 23.8 (range: 10–32) for focused attention and 22.4 (range: 15–42) for easy divided attention. For the K versus M comparison, mean trial counts for K waveforms in the difficult divided attention condition were 26.9 (range: 16–40). Mean trial counts for M waveforms were 25.1 (range: 13–49) for easy divided attention and 45.4 (range 36–56) for difficult divided attention.

3. Results

3.1. Behavioral results

3.1.1. Memory performance

Memory performance as a function of divided attention is depicted in Table 1. The percentage of items recalled in the free recall test declined when attentional resources were diverted from memorizing the words ($F(2,28)=55.4$, $P<0.0001$). Similarly, R responses declined systematically with the increased demands of the secondary task, regardless of how the probability of R responding was estimated. Although raw K hits corrected for false alarms did not show an effect of attention, a main effect of attention was found when the independent probabilities of R and K were analyzed, suggesting that K was also affected by reduced resources ($F(2,28)=102.0$, $P<0.0001$). Yet, this analysis also revealed a significant interaction between response

Table 1

Behavioral memory performance (shown as percentage) across the three levels of attention at encoding. In addition to raw hits and false alarm rates, the percentage of R and K responding is estimated using the independence assumption (R: Hits/[1–K], K: Hits/[1–R]; see text for further explanation). Standard errors are shown in parentheses

	Focused	Easy divided	Difficult divided
Recall (% correct)	36.3 (2.5)	27.2 (2.6)*	8.2 (1.2)*†
Remember			
Hits (raw)	63.0 (4.9)	53.0 (5.4)*	17.3 (3.0)*†
False alarms (FA)	0.8 (0.4)	1.2 (0.7)	1.8 (1.2)
Hits–FA	62.0 (4.7)	51.9 (5.2)*	15.5 (2.5)*†
Hits/(1–K)	81.8 (3.3)	69.9 (5.2)*	25.8 (4.5)*†
(Hits/[1–K])–FA	81.0 (3.2)	68.7 (5.0)*	24.1 (4.0)*†
Know			
Hits (raw)	24.2 (3.4)	25.4 (3.5)	33.7 (2.3)*
False alarms (FA)	11.6 (2.8)	12.6 (2.7)	20.4 (3.0)*†
Hits–FA	12.6 (3.8)	12.8 (3.9)	13.3 (2.4)
Hits/(1–R)	66.9 (3.8)	54.3 (3.9)*	41.1 (2.8)*†
(Hits/[1–R])–FA	55.3 (3.4)	41.7 (5.6)*	20.7 (2.7)*†

* Significantly different from focused attention ($P<0.05$).

† Significantly different from easy divided attention ($P<0.05$).

type and attention ($F(2,28)=18.2$, $P<0.0001$). Post-hoc comparisons indicated that this interaction was due to the effect of divided attention being much more deleterious to R than K.

Evaluation of the false alarm rate for R and K responses also demonstrated a main effect of response type ($F(1,14)=29.4$, $P<0.0001$) and a significant interaction between response type and attention ($F(2,28)=12.7$, $P<0.0001$). There was an increase in the percentage of K false alarms following difficult divided attention, indicating a general shift in response bias toward K responses in this condition ($F(2,28)=23.8$, $P<0.0001$). False alarm rates for focused and easy divided attention conditions did not differ from each other.

Participant strategy also changed as a function of attention at encoding. All but one participant reported an elaborative, imagery-based encoding strategy during the focused and easy divided attention conditions. All participants reported being unable to use this type of strategy under difficult divided attention. In this condition, participants reported that they used rote rehearsal or simply looked at the word and tried to ‘absorb it’.

On average, 92% of the items that were recalled on the free recall test were given an R response during the recognition test. Yet, subjects were able to ‘remember’ additional items on the recognition test that they could not recall. The proportion of remembered items that were recalled or not recalled did not differ as a function of encoding condition. Regardless of the level of attention at encoding, ~45% of ‘remembered’ items were only recognized (RO), and ~55% were additionally recalled (RR). There appeared to be no systematic differences in word frequency, length or semantic attributes between these two categories of ‘remembered’ items.

3.1.2. Secondary task performance

The greater demands of the difficult divided attention condition were also reflected in secondary task performance. Response accuracy was significantly higher in the easier task (95% versus 84% correct: $F(1,14)=13.6, P<0.005$), and the mean reaction time (RT) to the tones was significantly slower in the difficult divided attention condition (912 ms versus 786 ms: $F(1,14)=5.7, P<0.05$). Finally, the average RT when the difficult task was performed simultaneously with the memory task (dual-task) was 288 ms longer than when this task was performed alone (624 ms) ($F(1,14)=33.4, P<0.0001$).

3.2. Electrophysiological results

3.2.1. Overview

The grand mean ERPs at all electrode sites are shown in

relation to subsequent memory in Fig. 1 and in relation to the level of attention at encoding in Fig. 2. These ERPs were derived from the same data and therefore, the mean across the four memory categories (recalled/remembered, remembered only, known, missed) at a given time point from Fig. 1 is approximately the same as the mean across the three encoding conditions at the same time point in Fig. 2. Although the overall means are the same, the variance of the waveforms differs between the two figures indicating that memory and attention influenced the ERPs at encoding differently.

To simplify exposition of these differences we have divided our analyses into three sections: (a) *early peaks*, consisting of the early positive (P120) and negative (N180) deflections over the posterior regions of the scalp, (b) *later peaks*, which include a fronto-central positive peak at 200 ms (P200), a parietal-occipital positive peak at ~280 ms (P280), a focal left fronto-temporal negative wave peaking at ~340 ms (N340), and a parietal positive

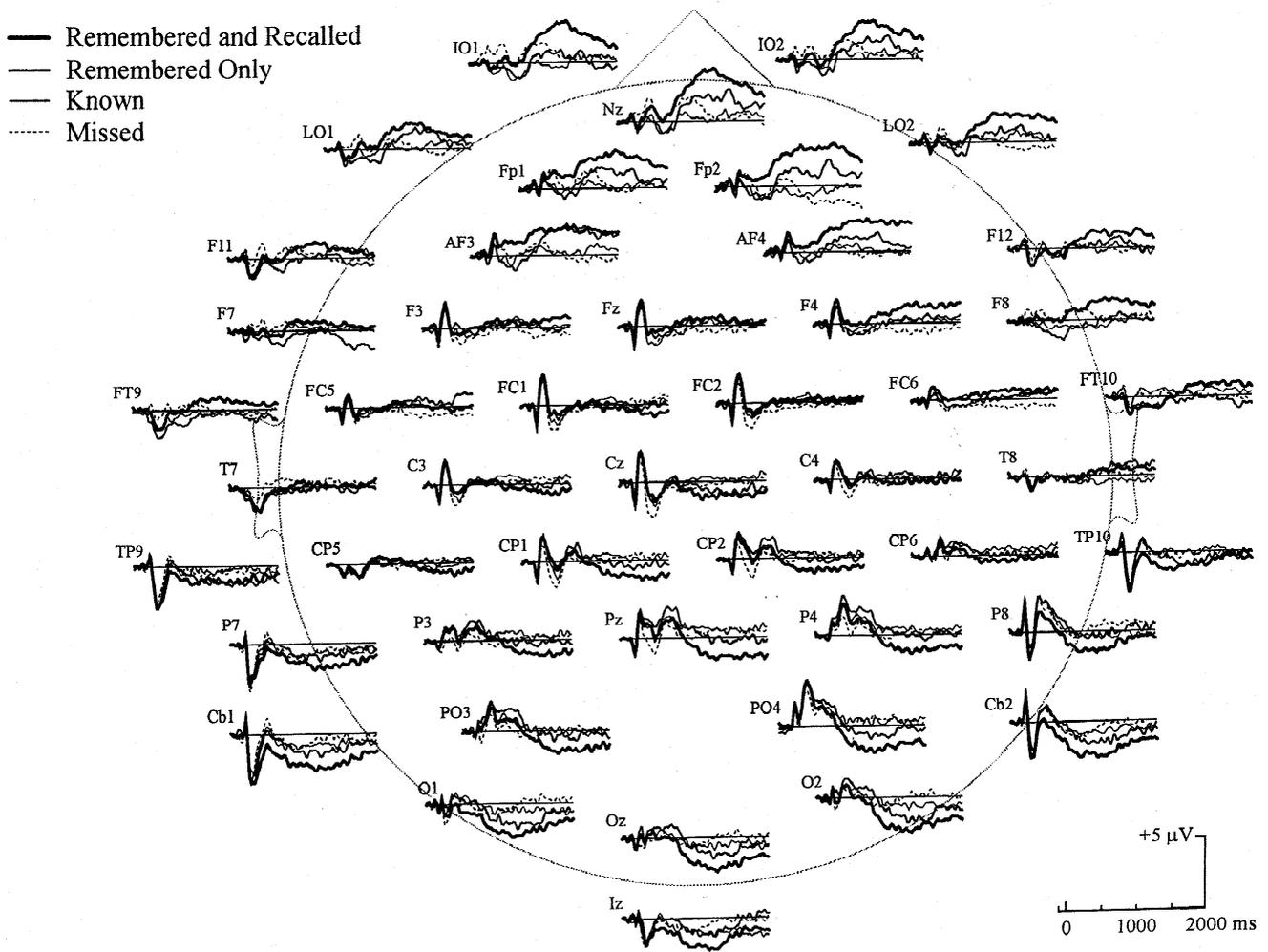


Fig. 1. ERPs at encoding associated with subsequently remembered and recalled (RR), remembered only (RO), known (K) and missed (M) items, collapsed across encoding condition, and shown at each of the 45 recording electrodes (neck electrode not shown). In this and all subsequent figures, ERPs represent grand mean data from the 15 artifact-free participants.

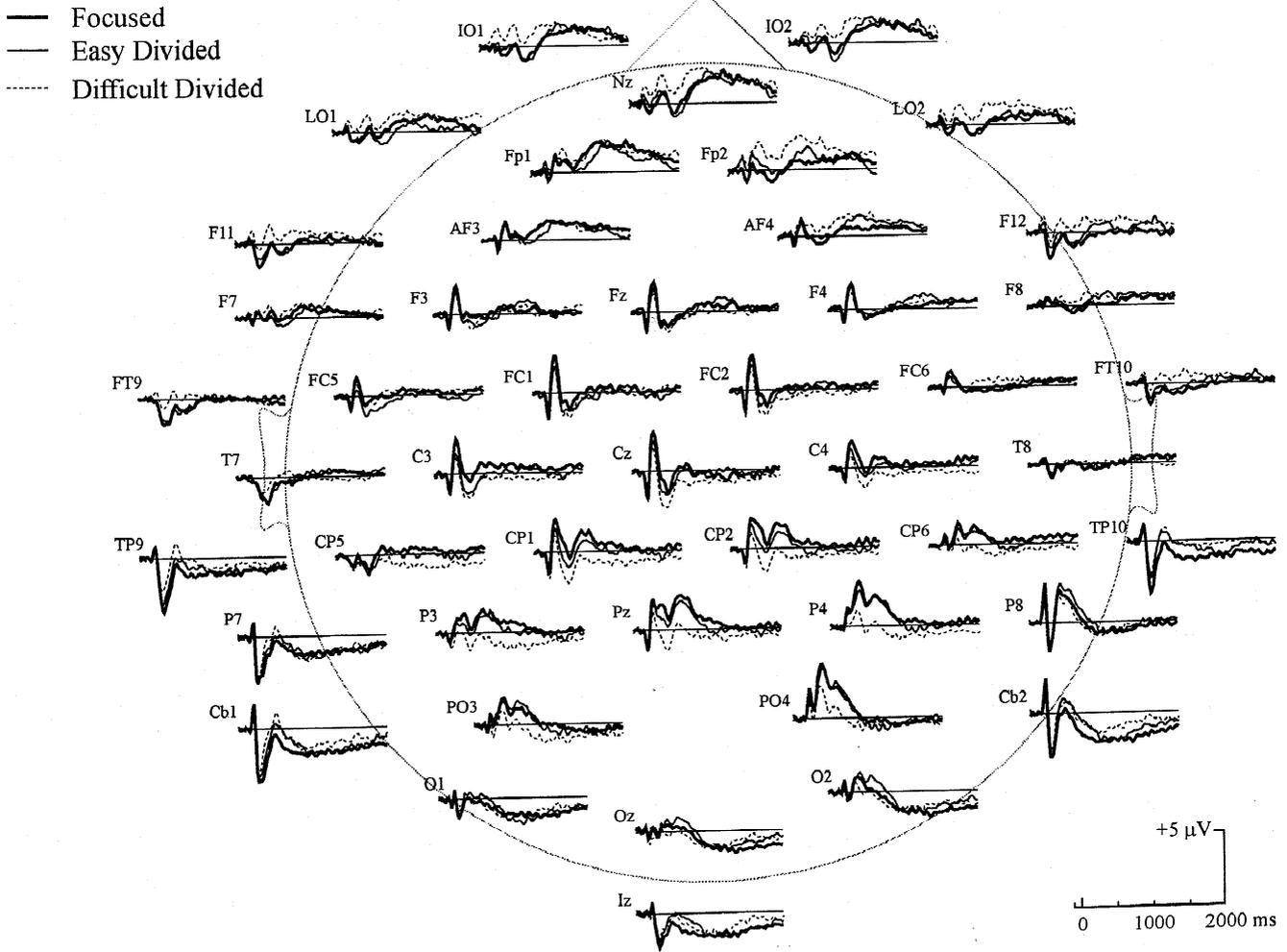


Fig. 2. ERPs associated with different levels of attention at encoding, collapsed across subsequent memory performance, and shown at each of the 45 electrodes (neck electrode not shown).

wave peaking at ~550 ms (P550), and (c) *sustained potentials* that began at ~200 ms post-stimulus and continued throughout the stimulus and were maximally recorded as positive in the front of the head and negative in the temporo-occipital regions. In general, the early peaks were more related to attention than memory, the subsequent posterior peaks were related to both attention and memory, and the sustained potentials were more specifically related to memory.

3.2.2. Early peaks

Fig. 3 illustrates the effects of attention and memory on the early peaks at their parieto-temporal maxima. The P120, which was larger over the right hemisphere ($F(1,14)=37.3, P<0.0001$), did not differ significantly as a function of subsequent memory, but was significantly affected by the manipulation of attention ($F(2,28)=4.4, P<0.05, \epsilon=0.94$). Focused attention produced a significantly larger response than difficult divided attention. The

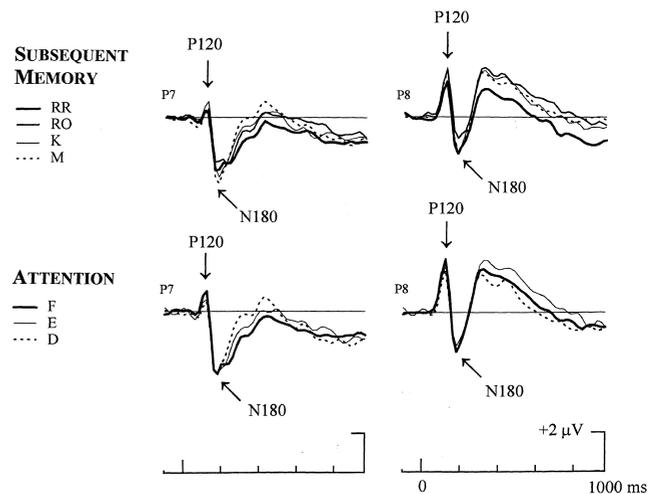


Fig. 3. The early peaks, P120 and N180, shown at the left and right temporo-occipital electrodes where these peaks were most prominent. ERPs were averaged as a function of subsequent memory or attention at encoding.

N180 was not significantly affected by either attention or memory. Although this peak demonstrated a significant left-hemisphere asymmetry ($F(1,14)=11.6, P<0.005$), there was no laterality effect in the peak-to-peak measurements between the P120 and N180. Thus, the apparent left-lateralization of the N180 was due to the strong right-lateralization of the P120–P280 waves upon which it was superimposed.

3.2.3. Later peaks

The relationship of the later peaks to memory and attention are shown in Fig. 4 at the left mid-temporal maxima of the N340 and the mid-parietal maxima of the posterior positive waves (P280, P550). At the fronto-central electrodes (FC1/FC2) where the P200 was maximal, there was a significant main effect of memory ($F(3,42)=5.6, P<0.005, \epsilon=86$). Post-hoc comparisons revealed that RR and RO items elicited greater fronto-central positivity than M items, but that K items did not differ from the other response categories. There was also a significant effect of attention ($F(2,28)=4.3, P<0.02, \epsilon=0.78$). Focused and difficult divided attention differed significantly from each other. The easy divided attention condition fell between these more extreme conditions.

The parietal-occipital P280 demonstrated a significant effect of memory ($F(3,42)=7.7, P<0.005, \epsilon=0.78$), hemisphere ($F(1,14)=28.8, P<0.0001$), and interaction between memory and hemisphere ($F(3,42)=1.1, P<0.05, \epsilon=0.62$). This was the first point of differentiation between items later known and missed. Specifically, over both right and left hemispheres, all items that were later successfully retrieved (i.e. RR, RO, K) elicited greater positivity than items that were missed. Additionally, RO items elicited significantly greater positivity over the right hemisphere than items that were also recalled (RR) or

given a K response. This peak was also sensitive to attention. Both focused and easy divided attention elicited significantly greater positivity than difficult divided attention ($F(2,28)=10.8, P<0.0001, \epsilon=0.90$).

The fronto-temporal N340 wave was significantly related to memory ($F(3,42)=3.6, P<0.05, \epsilon=0.70$), and left-lateralized ($F(1,14)=57.2, P<0.0001$). Post-hoc comparisons revealed that the N340 for items later retrieved was more negative than that for items later forgotten, but did not differentiate items based on the awareness associated with this successful retrieval ($R=K$). Analysis by attention revealed a significant interaction with hemisphere ($F(2,28)=4.9, P<0.02, \epsilon=0.88$). Over the left hemisphere, focused attention elicited significantly greater negativity than difficult divided attention; over the right hemisphere no significant effects were observed.

There was also a significant effect of memory on the P550 ($F(3,42)=4.6, P<0.02, \epsilon=0.87$). This effect was due solely to the enhanced positivity of the RO items relative to M items. RR and K items did not differ significantly from either RO or M items. The P550 also demonstrated a significant effect of attention ($F(2,28)=5.7, P<0.05, \epsilon=0.68$), resulting from reduced positivity in the difficult divided attention condition relative to the focused or easy divided attention conditions. Focused and easy divided attention did not differ significantly from each other. In addition, this wave demonstrated a significant right-hemisphere lateralization at P3/P4 electrodes ($F(1,14)=6.5, P<0.05$).

3.2.4. Sustained potentials

Fig. 5 illustrates the sustained potentials as they relate to attention and subsequent memory at their frontal (Fp1/Fp2) and posterior (Cb1/Cb2) maxima. Fig. 6 illustrates

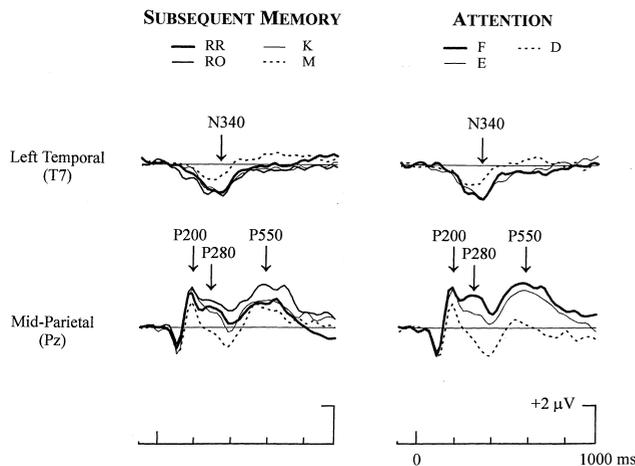


Fig. 4. Prominent positive and negative peaks occurring during the 200–800 ms latency range, shown at the left temporal (T7) and midline parietal (Pz) electrodes where these peaks were maximal. ERPs were averaged as a function of subsequent memory or attention at encoding.

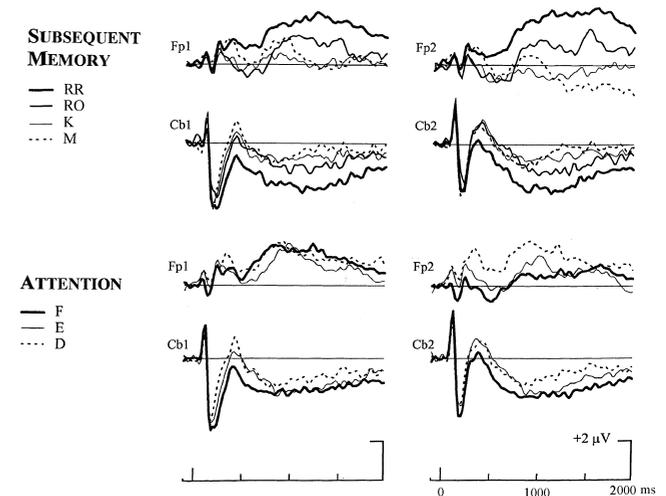


Fig. 5. Slow wave memory and attention effects over the frontal and inferior posterior electrodes where they were maximal (Fp1/Fp2; Cb1/Cb2).

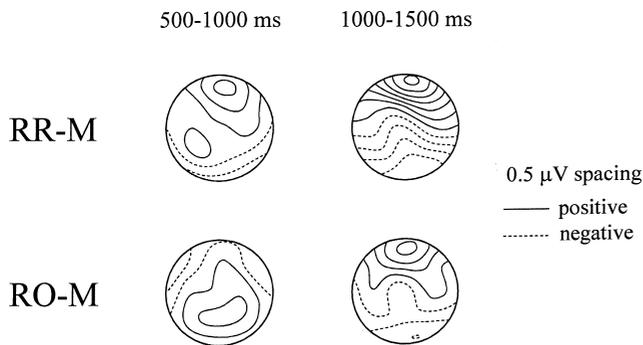


Fig. 6. Normalized scalp distributions of sustained potentials. Subsequent memory effects are based on the difference waveforms obtained by subtracting the ERP to missed stimuli (M) from the ERP to items that were subsequently recalled and remembered (RR) or remembered only (RO).

the normalized scalp distribution of the difference waves associated with subsequent remembering when it was and was not accompanied by successful recall.

The posterior negative sustained potentials showed no significant effects of attention. Yet, averaging on the basis of subsequent memory performance revealed significant differences throughout the encoding epoch. Main effects of subsequent memory performance were found from 500 to 2000 ms (500–1000 ms: $F(3,42)=10.0$, $P>0.001$, $\epsilon=0.60$; 1000–1500 ms: $F(3,42)=10.9$, $P<0.0001$, $\epsilon=0.65$; 1500–2000 ms: $F(3,42)=4.5$, $P>0.01$, $\epsilon=0.80$). In each of these time windows, RR items consistently elicited greater negativity than K or M items. K and M items did not differ from each other. The amplitude of RO items varied as a function of latency. From 500 to 1000 ms, the posterior sustained activity of these items was significantly less negative than RR items and overlapped with that of subsequent K or M items. During the 1000–1500 ms time window, however, RO items elicited significantly more sustained negativity than subsequent M items, but did not reliably differ from RR or K items. Finally, from 1500 to 2000 ms, the amplitude of the sustained negativity associated with RO items was not reliably different from any of the other item types.

Analysis of the sustained frontal positivity as a function of subsequent memory did not reveal significant differences between conditions until 1000 ms post-stimulus. From 1000 to 1500 ms, there was a significant main effect at the frontal poles (Fp1/Fp2) ($F(3,42)=3.9$, $P<0.05$, $\epsilon=0.72$). RR items elicited greater positivity than K or M items. RO items also elicited greater positivity than M items, but did not differ from K items. More posteriorly, at mid-frontal sites, a significant main effect of memory also was found (F3/F4) ($F(3,42)=5.2$, $P<0.05$, $\epsilon=0.80$). Post-hoc comparisons revealed that only RR items demonstrated reliably greater positivity than M items.

From 1500–2000 ms, a significant interaction between hemisphere and subsequent memory was found at mid-

frontal sites ($F(3,42)=3.9$, $P<0.05$, $\epsilon=0.47$). Over the right hemisphere, RR items elicited significantly greater positivity than K or M items, and RO items fell between RR and K items. There were no differences across item type over the left hemisphere. The effects were similar at the frontal poles, although here the effect was only a trend.

When evaluated as a function of attention at encoding, the frontal positivity was asymmetrically distributed over the left hemisphere during focused attention, but symmetrically distributed across both hemispheres during divided attention in the 500–1000 ms latency window ($F(2,28)=7.0$, $P<0.01$, $\epsilon=0.73$). This interaction was marginally significant from 1000 to 1500 ms ($F(2,28)=3.2$, $P=0.06$, $\epsilon=0.96$), but was not significant from 1500 to 2000 ms.

3.2.5. Memory effects at each level of attention

Because the number of words subsequently recalled and/or recognized varied with the different attentional conditions, it is possible that memory effects were confounded with attentional effects. The average waveform for subsequently recalled and remembered items contains more ERPs from the focused attention condition than from the divided attention condition. The reverse is true for subsequently missed items. To eliminate this confounding, we examined the memory effects separately for the different levels of attention at encoding. Because of the smaller number of trials in each memory condition when separated in this fashion, RR and RO trials were combined to form a single R category. Combining across these conditions was justified by the fact that the percentage of RR and RO items did not differ across encoding conditions, and by the qualitative similarity between the ERPs for these items (any differences being small and highly variable across time windows). In addition, we limited our comparisons to K versus M in easy and difficult divided attention and R versus K in focused and easy divided attention. All the waveforms are shown in the figures.

Memory effects at the parietal electrodes (i.e. P200, P280, P550) were not apparent when separated as a function of attention. The waveforms on the right of Fig. 7 show clear differences across attention but no differences within each level of attention. These results suggest that differences in the parietal positive components within the time window of 200–800 ms were more closely tied to modulations of attention than to memory-specific processes. Yet, as shown in the left of Fig. 7, memory effects remained generally stable for the N340 wave when separated as a function of attention. There were some small amplitude differences related to the increased noise in the tracings, however they were not statistically significant.

Fig. 8 illustrates the memory effects for the frontal and inferior posterior sustained potentials based on subsequent recognition. From 500 to 1000 ms post-stimulus, the difference between R and K items was larger under easy divided attention than under focused attention at both the

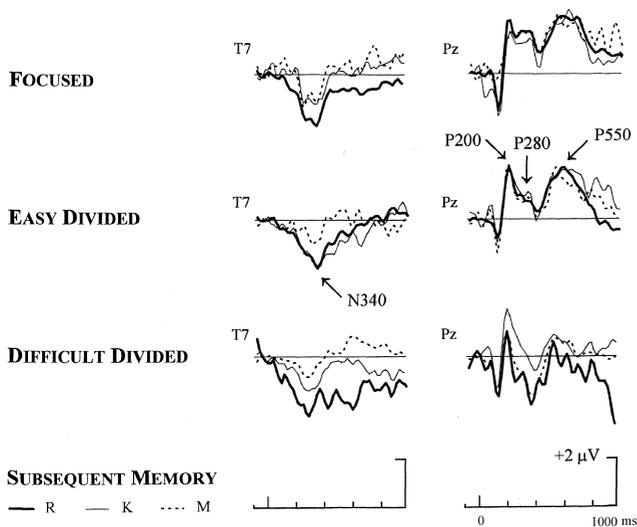


Fig. 7. N340 at the left mid-temporal (T7) electrode and the P550 at the midline parietal (Pz) electrode for subsequently remembered, known and missed items as a function of attention at encoding (focused, easy divided, difficult divided).

frontal poles (Fp1/Fp2: $F(1,14)=5.8$, $P<0.05$) and the temporal-occipital junction (Cb1/Cb2: $F(1,14)=8.3$, $P<0.05$). Specifically, when items were encoded under focused attention, slow wave activity at the frontal poles and inferior temporal region predicted successful retrieval, but did not strongly differentiate items on the basis of their phenomenological experience. When encoded under easy divided attention, however, slow wave activity at these sites clearly dissociated consciously recollected items (RR and RO) from those retrieved on the basis of familiarity alone (K). In this condition, those items that were merely familiar at test demonstrated no greater sustained activity than did those that were subsequently forgotten (M). This difference was accentuated in the mean waveforms for the

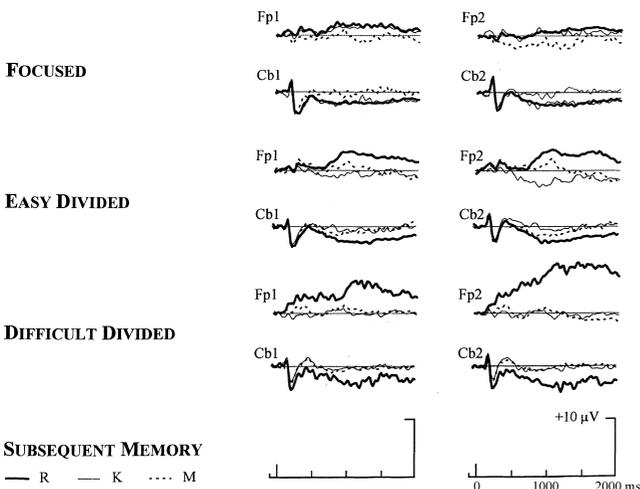


Fig. 8. Sustained activity at frontal (Fp1/Fp2) and inferior posterior (Cb1/Cb2) sites for subsequently remembered, known or missed items, as a function of attention at encoding.

difficult divided attention condition although there were too few trials for statistical analysis.

4. Discussion

4.1. Overview

The present study used the event-related potentials (ERPs) to delineate a sequence of cerebral processes that occur when a word is encoded into episodic memory and to determine how attention affects this sequence. The amount of attention available for encoding was manipulated using a secondary task with two levels of difficulty. Reduced attention to the encoding task impaired episodic memory, as measured by either free recall or the proportion of items recognized with conscious recollection of the encoding context (R). Although divided attention also reduced the proportion of items recognized without recollection of this context (K) when estimated using the independence assumption, this effect was smaller relative to its effects on conscious recollection.

The effects of attention on encoding processes could also be observed in three distinct patterns of ERP waveforms: (a) waves that were related to attention but not related to subsequent memory (P120), (b) waves related to both attention and memory (N340, sustained frontal positivity), (c) waves that were related to both attention and memory but did not show effects of memory when examined within each level of attention (P200, P280, P550). Waves demonstrating the first and third pattern represent processes that can be facilitated by attention, but do not specifically predict later episodic retrieval. The processes indexed by these waveforms may be necessary for episodic encoding, but the level of processing afforded under divided attention was sufficient to process information adequately through this stage. Waves exhibiting the second pattern indicate processes that are both modulated by attention and predictive of successful long-term episodic memory. The locus of these waves in the encoding sequence should indicate the timing, and to some extent the location, of the attenuating effect of divided attention on episodic encoding.

In the discussion that follows, we first describe these ERP waves in the sequence in which they occur, along with their hypothesized cognitive and neural correlates, which are summarized in Table 2. On the basis of these interpretations, we then discuss their implications on the theoretical relationship between recall, conscious recollection and familiarity.

4.2. Physiological processes

4.2.1. Early peaks related to stimulus perception

The parieto-occipital P120 and N180 waves were the

Table 2
Summary of ERP component sequence with proposed cognitive and neural correlates^a

ERP sequence	P120/N180	P200/P280	N340	P550	Sustained potentials	
					Posterior	Frontal
Memory effects						
Remember			+		+	+
Know			+			
Attention effects						
Easy						
Difficult	–	–/–	–	–		+
Psychological process	Perceptual analysis	Selection/awareness	Conceptual analysis	Memory registration and/or updating working memory	Maintenance of representation	Central executive
Cerebral source	Extrastriate/fusiform gyrus	Frontal-parietal loop	Left inferior frontal and/or anterior temporal	Parietal-MTL/H loop	Inferior temporal (ventral stream)	Prefrontal

^a Memory effects are indicated as an enhancement related to subsequent memory performance. Memory effects are shown if they were both demonstrated in the averaged data and clearly found under easy divided attention. Attention effects show where the secondary task causes a decreased amplitude (–) of the ERP. The exception to this pattern was the increased (+) amplitude associated with supervision of the dual tasks. The tabulated sources and processes are hypothetical MTL/H–medial temporal lobe/hippocampus. See text for further explanation.

first prominent peaks in the encoding ERP and most likely represent early, lateralized processes involved in the initial perception of verbal stimuli [70]. Previously, the right-lateralized P120 has been associated with both pre-lexical feature detection [7], and early lexical processing [82]. The left-lateralized N180, however, consistently demonstrates differential sensitivity to word form [7]. For example, Nobre et al. [57] have described potentials in the posterior fusiform gyrus that were only found for letter strings and might underlie the scalp-recorded N180 to words.

Numerous studies have demonstrated that the P1 and N1 are enhanced by selective attention to spatial location (for review, see Ref. [50]). The effects of the dual-task on the P120 in the present study suggest that it can be influenced by manipulations of central attentional resources, as well. Yet, like the N180, the P120 was not clearly related to subsequent memory. Although perceptual processing is necessary for a declarative memory trace to be formed, it appears that attentional facilitation beyond a threshold sufficient to reach subsequent stages has little effect on later memory.

4.2.2. Later peaks

4.2.2.1. P200, P280 and stimulus selection. The P200 and P280 were significantly affected by attention, but did not appear to vary with subsequent memory. Based on this pattern and findings from previous ERP studies, we suggest that these positive components reflect processes associated with initial selection of the word from competing stimuli for further processing in working memory. For example, a component with a similar distribution and latency to the P200 appears to represent the first differentiation of spatial and verbal working memory tasks from perceptual control tasks [1,30]. Chapman et al. [6] also associated a centroparietal positive peak at 250 ms with

access of information to ‘short-term storage’. Although less is known about components with the latency and distribution of the P280, Rudell et al. (e.g. Ref. [78]) have described an occipital potential peaking slightly before 300 ms, which they termed the ‘recognition potential’. It is only evoked by information that is attended and meaningful to the subject, as it is not evoked by words that are not in the subject’s native language. Yet, although selection requires attentional resources and is necessary for information to be encoded into declarative memory, selection does not ensure that a retrievable long-term memory trace will be formed.

Posner and coworkers [71,72] have proposed a network for visual selective attention that involves both frontal and posterior cortices and may provide a framework for interpreting the cognitive correlates of the P200 and P280. In Posner’s model, medial frontal regions, including the anterior cingulate, are part of a voluntary attention system that determines where and how attention should be directed to meet the demands of a particular task. The posterior parietal regions then engage attention in the local area where this information can be found. Recent evidence suggests that P200 waves occurring during visual word reading [1] and auditory processing [67] might be generated (at least partly) in cingulate regions. Although we did not conduct source analysis in the present study, the bilateral, central distribution of our P200 also could be consistent with a cingulate source. Thus, the P200 and parietocentral P280 may represent the contributions of the anterior and posterior attentional networks, respectively, to the selection of the word for further processing.

4.2.2.2. N340 and semantic processing. The N340 wave was affected by both attention and subsequent memory, indicating that it represents an attentionally-modulated process that also is predictive of successful encoding.

Items retrieved with conscious recollection of the episodic context (i.e. recalled and remembered, remembered only) elicited an enhanced N340 relative to later missed items across all levels of attention. When ERPs were averaged over encoding condition, items subsequently recognized on the basis of familiarity (K) also elicited a larger N340 than missed items, and at least under conditions of easy divided attention, elicited an N340 similar to remembered items. We wish to note that easy divided attention provided a sufficient number of trials for averaging in all response conditions, and is probably more representative of the mild distraction present during everyday learning situations than either the focused or difficult divided attention.

Many previous findings point toward a relationship between the N340 and lexical and/or semantic processing. Kutas et al. [43,47] have described a 'lexical processing negativity', a left fronto-temporal negative wave with a peak latency that varies inversely with word-length and frequency in the range of 280–340 ms, and a 'left anterior negativity' that occurs 300–500 ms after words requiring complex syntactic processing (e.g. in subject–object relative sentences [44]). Regarding semantic processing, Nobre and McCarthy [58] found an early left fronto-temporal negativity (N316) that was enhanced when a preceding item was semantically related. In addition, intracranially recorded ERPs have demonstrated positive relationships between both semantic processing or verbal memory and left temporal negative potentials with peak latencies near 400 ms [15,32,59]. It is unlikely, however, that the N340 is a manifestation of the classic N400 wave associated with semantically incongruous stimuli, as this wave is maximally recorded over the right parietal scalp [48], and has not been shown to be predictive of later memory [56].

Our view is that the N340 wave most likely represents attention-dependent conceptual processing of words in either temporal and/or inferior frontal neocortex. This interpretation is further supported by studies of cerebral blood flow demonstrating activation of left inferior frontal and left middle temporal cortex during conceptual, as opposed to simple perceptual processing [24,41] and a recent PET study showing a decrease in the blood flow to left inferior prefrontal regions when attention was divided at encoding [37].

4.2.2.3. P550, attention and working memory. The amplitude of the P550 was greatly attenuated under difficult divided attention, but the effects of memory on this component were relatively small. Although we lacked sufficient trials to separate RR and RO items across attentional condition, the relationship of this wave to memory did not appear to persist when the ERPs were considered within each attentional condition. Similar dissociations between attention and memory have been found at the parietal-maximal P3b, a waveform with a latency and distribution similar to the P550. For example, in a

short-term serial recall task, Grune et al. [31] found that the amplitude of P3b declined as working memory load increased from one to seven letters, but was not associated with subsequent memory.

Based on previous studies, we suggest that P550 marks either the completion of the earlier processes in sensory and multimodal association areas involved in decoding the task-relevant meaning of the item [92], and/or registration of this information in declarative memory through operations performed by the medial temporal lobe/hippocampal complex MTL/H [33,34]. Many of the processes involved in decoding and registering the stimulus are attention-dependent, therefore it is likely that the P550 would also be sensitive to the amount of available attentional resources. Yet, it is possible that later retrieval depends mainly on the content of the registered memory rather than the actual registration process. This idea is speculative, but it would allow later retrieval to vary with the N340 and not with the late positive wave. The P550 also may index the updating of working memory with the newly formed item representation [13,66]. This updating would be necessary for relational processing with other items in working memory. Relational processing may be represented by the frontal sustained potentials, which emerge during the P550 component and reach their maximal amplitude when the P550 returns to baseline.

4.2.3. Sustained potentials

4.2.3.1. Posterior negative sustained potential and the ventral visual stream. The posterior negative sustained potential, which demonstrated a clear association with subsequent memory, may indicate sustained activation of object representations pertaining to the concrete object the word represented or the word itself. Numerous studies with human and non-human primates have shown that the ventral posterior portion of the brain, extending from extrastriate cortex to inferior temporal regions, participates in the processing of visual object information [52,90]. Furthermore, Smith and Halgren [85] found a visual processing negativity with a similar distribution during a visual recognition test for words, which was attenuated by temporal lobe lesions, and proposed a bilateral inferotemporal generator for this memory-related potential. Yet, with the exception of one study of face processing [86], significant Dm effects with a posterior–inferior distribution have not been reported. This may be due, in part, to differences in recording techniques. We elected to use an average reference rather than a mastoid or earlobe reference, which are commonly used in Dm studies [19,56,62,63,91]. The effect of using a mastoid reference can be visually estimated by comparing the TP9/10 waveforms with those of posterior electrodes in Fig. 1. The clear sustained negativity at mastoid electrodes Tp9/10

would be subtracted away from negativity recorded at the posterior electrodes if a mastoid reference had been used.

4.2.3.2. Sustained frontal positivity, elaboration and the central executive. As predicted, subsequently remembered and recalled words elicited a robust sustained frontal positivity similar to that found in previous ERP studies where encoding processes were explicitly biased toward elaborative, associative strategies [19,94]. These findings provide further support for the hypothesized relationship between the frontal positive wave and the cerebral activity necessary for elaborative processing. This interpretation also gains support from a number of behavioral studies in patients with focal lesions demonstrating the importance of this region to both strategic processing and successful episodic memory performance (e.g. Ref. [88]).

What could be the nature of these elaboration processes? ‘Remembering’ involves retrieval of some aspect of the context experienced at the time of learning, although the precise type of context is not specified. Indeed, conscious recollection may draw upon multiple types of elaboration at encoding, including imagery, associations with other list items, and associations with pre-existing information in semantic and episodic memory [29]. Changes in the hemispheric distribution of the frontal positivity across the encoding epoch support the possibility that several elaborative processes may have occurred during the course of memorizing the words. Under optimal episodic encoding, significant left frontal positivity was found during the earlier part of the encoding epoch. This left-frontal sustained activity may index conceptual processes involved in establishing associations between the item and related information stored in semantic memory. Later in the epoch, however, the frontal memory effect for recalled and remembered items was larger over the right-hemisphere. This right frontal positivity might index retrieval and comparison processes involved in the strategic organization of list items. Indeed, both previous ERP [81,97] and blood-flow studies (e.g. Refs. [4,60,80]) have found right-frontal activity during episodic retrieval and evaluation processes. Retrieval processes would be necessary to access list items that were no longer within the immediate focus of attention, and comparison processes would participate in relating these items together. In addition, this right frontal sustained potential may represent the processing of a word in relation to personal context. In support of this interpretation, recent neuroimaging evidence has shown the differential involvement of right frontal regions in self-referential encoding processes [10]. The spontaneous association of an item to one’s personal history could occur even when a participant does not engage in more strategic forms of encoding [77], thereby supporting the episodic encoding of a few items even under demanding divided attention conditions.

Notably, although right-lateralized or bilateral frontal activity during successful encoding is common to ERP

studies [51,62,84,91,94], it contrasts with the typical pattern of left-lateralized frontal activity found in similar PET studies. Differences in the distribution of frontal activity found in PET and ERP studies may be related, in part, to differences in the type of encoding-related activity revealed by blocked versus selective averaging. Indeed, in the present study, ERPs averaged across the focused attention block (rather than selectively averaged) demonstrated the left-lateralization common to PET studies of verbal episodic encoding [5]. It is possible that the blocked averaging of PET reveals activity associated with a general encoding mode, whereas the selective averaging of ERP reveals something more specific about processes that predict later memory.

It also may seem contradictory that the sustained frontal positivity associated with successful episodic encoding was enhanced under difficult divided attention — the condition where episodic memory performance was the poorest. One possibility is that the frontal positivity apparent in these two averages represents activity from two anatomically and functionally distinct, but adjacent sources in the prefrontal cortex. For example, in a recent PET study by Iidaka et al. [37], divided attention not only decreased blood flow to an inferior left-frontal region (BA 47), but also increased activation in the nearby middle-frontal gyrus (BA 46/9) of both hemispheres. On the other hand, the frontal positivity observed in both the Dm and attention analysis may represent a common anatomical and functional source — the operations of the central executive in working memory. By this view, the frontal Dm effect indexes the operations of the central executive for the purpose of strategic organization of representations in posterior regions. The frontal positivity observed when ERPs were averaged by attention may index the supervisory operations of the central executive required to monitor and switch attention across the primary and secondary tasks.

4.3. Psychological processes

4.3.1. Remembering vs. knowing

Items that could be both recalled and remembered were associated with greater frontal positivity and inferior temporal negativity than subsequently known or missed items. These results extend earlier findings of enhanced frontal positivity for words successfully recalled and remembered [42,94], by demonstrating that these frontal regions do not operate in isolation, but rather, interact with representations maintained in the posterior ventral stream. Notably, items that could be remembered, but not recalled, also generated activity in these regions, but this activity was smaller in magnitude, shorter in duration and generally more variable. These results suggest that although processing which is less consistent cannot provide the level of organization necessary for free recall, R responses are not purely dependent on relational processing. Items that

are subsequently remembered, but cannot be recalled appear to derive conscious recollection from item-specific processes indexed by the N340 and perhaps also the P550.

Although items later recognized on the basis of familiarity (K) did not consistently demonstrate the enhanced frontal positivity or inferior posterior negativity associated with conscious recollection (R), these items could be differentiated from items later forgotten at the N340. Given our interpretation of the N340 as an index of semantic processing, this differentiation would suggest that K is conceptually based, at least in part. This interpretation also fits with our behavioral data, which demonstrates an effect of attention of K responses, as well as R, when probabilities are estimated using an independence assumption. Conceptual processing is reduced by divided attention [8,37], and therefore conceptually-based K responses should be affected by reduced attentional resources. Yet, K responses may be less affected by divided attention than R because K responses can also be derived from processes underlying perceptual fluency.

These results are in line with recent evidence indicating that K responses are not limited to perceptual fluency and can represent conceptual processing and the operations of a declarative memory system [74,75]. For example, Rajaram [74] found that some types of perceptual mismatch resulted in an increase of K responses rather than the decrease that would be expected if K were equivalent to perceptual priming. In addition, Knowlton and Squire [46] demonstrated that amnesic patients with lesions in the medial temporal lobe — a structure critical for storage in declarative memory — demonstrate impaired levels of both R and K responses on a recognition test, although K was less affected. Similar results were found across a range of remember-know tasks with temporal lobe amnesics when the high false-alarm rates typical of the amnesic patients were taken into account using receiver-operating characteristics (ROCs) [98].

Together, the relationship between R and K at the N340 and the sustained potentials indicate that the processes underlying R and K are redundant, at least at encoding. Specifically, during the first 400 ms of stimulus encoding, perceptual and conceptual processes take place that are sufficient for establishing a declarative memory trace that can be recognized on the basis of familiarity (K). Such processing is necessary, but not sufficient, for conscious recollection (R), which appears to require either additional associative encoding, as indexed by sustained frontal and inferior temporal activity (500–2000 ms), or increased attention to distinctive, item-specific features, as indexed by a more transient process (P550) that correlates with the amount of attention allocated to the stimulus.

4.3.2. *Knowing as a function of attention*

As stated previously, when K was estimated using the independence assumption, it appeared to be affected by divided attention, though to a lesser extent than R. ERP

indices predictive of K responses also appeared to vary with the allocation of attentional resources. Specifically, R/K differences at the frontal and inferior sustained potentials were larger under easy divided attention than under focused attention, and K/M differences in the N340 were larger under easy divided attention than under difficult divided attention. These variations support the view that not all K responses were derived from the same encoding processes. In the following section we provide some hypotheses for why these differences may have occurred.

In the focused attention condition, sustained potentials associated with subsequent R and K responses did not differ from each other. Indeed, the actual effect size of K response may be larger than R, given that the higher false alarm rate of K responses relative to R responses suggest that this ERP category included 'lucky guesses', as well as veridical retrieval. Given that under focused attention there is no distracting task to interfere with conceptual processing or subsequent elaboration, the lack of difference between R and K in this condition may have occurred because participants categorized an item as R or K on the basis of the relative strength of the association between content and context, rather than on whether this association has occurred or not at encoding. To the extent that ERPs are not able to index subtle differences in association strength, subsequently remembered and known items would demonstrate equivalent (or near equivalent) slow wave activity, as shown in Fig. 8. Yet, the strength of the association created during encoding might predict the extent to which it would be susceptible to interference from subsequent items or decay subsequent to encoding, which would not have been evident in the 2 s of stimulus encoding when the ERPs were measured.

When there was mild distraction during encoding (i.e. easy divided attention), qualitative differences in frontal and posterior slow waves emerged between subsequently remembered and known items, although the N340 for these items was equivalent. These findings fit with the neurocognitive model of Moscovitch and Umiltà [53] which proposes that a minimal drain on resources should not greatly interfere with the conscious apprehension and basic semantic processing of most items, although it will make engaging in elaborative, organizational processes more difficult. The severe reduction in processing resources during the difficult divided attention condition, however, not only may have interfered with elaboration, but also with basic conscious apprehension and semantic processing of the information [54]. Thus, it is possible that in the difficult divided attention condition participants may have judged more items as familiar on the basis of perceptual fluency, similar to the fluency underlying perceptual priming, rather than on the basis of conceptual fluency.

To the extent that the N340 is an index of conceptual processes involved in declarative memory storage, the inclusion of perceptually-based K responses in the average

for subsequently known items would reduce the amplitude of the averaged K items. Although the difference between subsequent K and M items within this latency range did not differ statistically between the two divided attention conditions, under difficult divided attention the amplitude of the N340 for subsequently known items was numerically smaller than under easy divided attention. With a greater number of trials this difference may have been significant. Future ERP studies may serve to elucidate this issue further by decomposing the K response category into responses that are knowledge (conceptually) or attribution (perceptually) based, and by including a guessing category at test.

In summary, we suggest that the ERPs associated with subsequent K responses varied with attention at encoding because the relative contributions of conceptual and perceptual processing may be influenced by participants' metamemory for the global strength of the memory traces from the relevant encoding episode. Behavioral studies have shown the relative proportion of K responses can be biased by testing parameters, including the participants' beliefs about the base-rate of target items [35,87]. The present study suggests that participants may also change their criteria for K responses to reconcile knowledge about the proportion of targets in the recognition test list (0.50) with knowledge about the accessibility of memorial information (e.g. less accessibility in difficult divided attention relative to focused attention condition). Yet, qualitative differences in the ERPs for R and K as a function of attention at encoding suggest that this change does not occur on a single dimension, such as trace strength. Rather, participants' metamemory for the global strength of memory traces from that encoding episode may influence the relative contribution of conceptual and perceptual processes to 'knowing'. Indeed, given that R and K fundamentally represent metamemory judgments regarding quality of the retrieval experience, they may be influenced by metamemory for the encoding experience, as well. This interpretation could be addressed by an ERP study in which subjects retrieve items encoded under focused, easy and difficult divided attention in a single recognition block. In this situation, the average memory strength of the pool should approach that of the easy divided attention condition and the pattern of Dm effects presently found under this condition should occur regardless of the level of attention under which the items were encoded.

5. Conclusions

Analysis of the ERPs associated with attention and subsequent memory revealed a sequence of components that represent cognitive processes underlying the decoding and encoding of verbal information into episodic memory. We have proposed the following interpretation of these components (see Table 2). Following initial perceptual

analysis of the word stimulus (P120, N180), the item is selected as task-relevant and becomes available for conscious processing (P200, P280). The subsequent fronto-temporal negativity (N340), which was both sensitive to attention and predictive of subsequent memory performance, may represent a final stage in semantic processing of the item. Upon completion of item-specific processing, this consciously apprehended information may become accessible to the medial temporal lobe/hippocampal (MTL/H) region for subsequent storage in long-term memory (P550) and is added to the contents of working memory for further processing. Relational, elaborative, processing of this information, which is necessary for successful strategic retrieval on a test of free recall, is largely determined by the sustained interaction of frontal and inferior temporal regions, which begins at ~1000 ms.

Attention within the first 800 ms of processing is necessary to establish a semantic representation that can later be consciously accessed on a test of explicit memory. When there is a severe reduction in attentional resources, as in the difficult divided attention condition, there is a decline in conscious awareness of the stimuli, marked by attenuation as early as the P120 and continuing through the P200, P280 and P550. Impaired conscious awareness of the stimulus may decrease the likelihood that storage processes in left medial temporal regions will pick up this information and increase the proportion of missed items. The proportion of known items may not appear to change, however, because some know responses depend on perceptual fluency and, like data-driven implicit memory, arise from the reactivation of early perceptual processes.

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