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Event-related potentials and serial position effects in a visual probe recognition task

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Abstract

In two experiments, we explored the utility of using event-related brain potentials (ERPs) evoked during picture recognition to examine the cognitive and neural processes underlying primacy and recency effects. Each experiment consisted of 210 trials in which a recognition probe followed a 12-picture sequence (105 match and 105 nonmatch trials). The 105 match-probe trials consisted of 35 trials in which the probe matched a prime memory set item (Positions 1–3), 35 in which the probe matched a middle memory set item (Positions 6–8), and 35 in which the probe matched a recent memory set item (Positions 10–12). Behavioral results revealed recency but not primacy effects in both experiments. Recent probes, compared with prime and middle probes, evoked ERPs that were more positive from approximately 300 to 400 ms; this enhanced positivity occurred in a positive component peaking around 315 ms and a negative component peaking around 365 ms. These findings fit more closely with the notion of short-term memory as an activation of elements in long-term memory than as a distinct memory store (or stores) separate from long-term memory.

Descriptors: Serial position effects, Serial probe recognition, Visual memory, Recency effect, Event-related potentials

In one of 14 invited articles commemorating the centennial of Hermann Ebbinghaus's seminal 1885 treatise, Murdock (1985, p. 470) lamented that Ebbinghaus had the misfortune to have tackled serial-order phenomena—"the most intractable and least well understood even today" aspect of human memory. Although Ebbinghaus focused on serial learning and developed an associative chaining hypothesis that is seldom invoked today, he made a lasting contribution by recognizing that an explication of serial-order phenomena is essential for theories of learning and memory. Subsequent research has concentrated on the ubiquitous serial-order phenomena of preferential memory for items located at certain serial positions, which according to Stigler (1978) was originally described by Nipher in 1878. This serial position effect is generally hypothesized to be due to enhanced memory for items presented near the beginning (primacy effect) and end (recency effect) of a memory set compared with that for items presented in the middle of a memory set.

In spite of an array of methodologies for examining memory and serial memory effects (for a review, see Richardson-Klavehn & Bjork, 1988), an understanding of the cognitive and neural mechanisms underlying primacy and recency remains elusive. For instance, prominent early theories attributed the preferential memory for items presented recently in a memory set to their presence in a short-term store of limited capacity and duration (Atkinson & Shiffrin, 1968; Waugh & Norman, 1965). The recency effect, in fact, provided a basis for the modal model of memory that differentiated short- and long-term memory stores. Findings demonstrating preferential memory for recent items not present in a short-term store, however, challenged the modal model's explanation of recency (e.g., Baddeley & Hitch, 1977; Roediger & Crowder, 1976; Tzeng, 1973; Watkins & Peynircioglu, 1983; for more detailed discussions, see Greene, 1986; Healy & McNamara, 1996). This led to revisions of the modal model (e.g., Raaijmakers & Shiffrin, 1981) and to alternative explanations for the recency effect including, for example, distinctiveness (e.g., Johnson, 1991; Murdock, 1960; Neath, 1993), priming (Baddeley & Hitch, 1993), and trace features (Nairne, 1988, 1990). This abundance of rival explanations, as well as the contentiousness of the theoretical discourse concerning the recency effect (e.g., see Baddeley & Hitch, 1993; Crowder, 1993), illustrates that we still do not have a good understanding of the cognitive processes underlying the recency effect in particular and serial position effects in general. The purpose of the present experiments was to examine the event-related brain potentials

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(ERPs) associated with recognition judgments to ascertain whether ERPs can potentially be used to examine the cognitive and neural mechanisms underlying primacy and recency effects.

Since the 1960s when much of the research on serial position effects was conducted, research using ERPs has established that the amplitude and the latency of ERP components can be used to investigate memory processes. For example, when people do not expect an ensuing memory test or use a rote memory strategy, items that are subsequently recalled are associated with a larger P3 component of the ERP (also referred to as P300, P3b, or late positive component or potential) than are items that are not subsequently recalled (e.g., Fabiani, Karis, & Donchin, 1986, 1990; Karis, Fabiani, & Donchin, 1984). Thus, the amplitude of the P3 seems to reflect the activity of a subset of neural and cognitive processes associated with encoding information into memory. Other research suggests that the latency of the P3 can assess the time it takes to search short-term memory (STM) and categorize a stimulus as either present or absent from STM. That is, when people are required to indicate whether a probe item is present in STM, the latency of the P3 to the probe increases as the number of items in STM increases (Adam & Collins, 1978; Ford, Roth, Mohs, Hopkins, & Kopell, 1979; but see Pelosi, Hayward, & Blumhardt, 1995). Furthermore, research using both P3 latency and reaction time to investigate age-related slowing of behavioral responses during memory scanning has revealed that slowing response processes and not slowing categorization processes are the principal cause of this age-related slowing (Ford et al., 1979; Pratt, Michalewski, Patterson, & Starr, 1989; Strayer, Wickens, & Braune, 1987).

A substantial body of research using ERPs to investigate memory has compared ERPs evoked by "old" stimuli (i.e., seen previously during the experimental task) and "new" stimuli (i.e., not seen previously during the experimental task) (for reviews, see Kutas, 1988; Rugg, 1995). This research has demonstrated that ERPs evoked by old stimuli are more positive from approximately 250 to 600 ms than are ERPs evoked by new stimuli. Furthermore, these old/new effects occur in (a) continuous recognition tasks in which participants indicate whether each stimulus has been presented previously (e.g., Berman, Friedman, & Cramer, 1991; Chao, Nielsen-Bohlman, & Knight, 1995; Friedman, 1990a, 1990b; Rugg & Nagy, 1989), (b) list-learning tasks in which participants learn a list of words over which they are subsequently assessed (e.g., Johnson, Pfefferbaum, & Kopell, 1985), (c) match/mismatch tasks in which participants decide whether a stimulus matches or does not match the preceding stimulus (e.g., Barrett, Rugg, & Perrett, 1988), (d) incidental learning tasks in which participants are asked to identify stimuli to which they were previously exposed with no expectations regarding subsequent memory assessment (e.g., Paller & Kutas, 1992; Rugg & Doyle, 1992), (e) sentence repetition tasks in which participants are exposed to a sentence whose terminal word either matches or does not match a terminal word used previously (e.g., Besson, Kutas, & Van Petten, 1992; Mitchell, Andrews, & Ward, 1993), and (f) implicit memory tasks in which participants categorize stimuli along various (e.g., semantic) dimensions (e.g., Bentin, Moscovitch, & Heth, 1992; Bentin & Peled, 1990).

Several experimenters have examined whether ERPs evoked by old stimuli vary according to the number of items that intervene between the first and second instance of the stimulus. Rugg and Nagy (1989), for example, conducted a continuous recognition task in which either six or 19 items intervened between the first and second instance of each stimulus. They found that the old/new ERP differences did not vary according to the number of intervening items (i.e., the magnitude of the old/new effects was the same regardless of whether six or 19 items separated the two presentations). To examine whether the presence or absence of an item in STM influences old/new effects, Friedman and colleagues (Berman et al., 1991; Friedman, 1990a, 1990b) conducted continuous recognition experiments in which 2, 8, or 32 items intervened between the first and second instance of a stimulus. Their results also revealed that the old/new ERP differences did not vary according to the number of intervening items, and thus these results imply that ERPs are not influenced by the presence versus absence of an item in STM. These findings may have limited applicability for addressing serial position effects, however, because the cognitive processes required in continuous recognition tasks may differ from those required in memory tasks that give rise to serial position effects. For example, when participants in a continuous recognition task encounter a stimulus, they may initiate parallel cognitive processes for searching memory and encoding the stimulus into memory. Participants in a serial-probe recognition (SPR) task, however, need only initiate memory search processes when they see a probe stimulus.

Given the prevalence and importance of serial position effects, demonstrated by the fact that similar serial position effects occur in pigeons, monkeys, and humans (Sands & Wright, 1980; Wright, Santiago, Sands, Kendrick, & Cook, 1985), there has been surprisingly little research using ERPs to examine serial memory effects. Patterson, Pratt, and Starr (1991) recorded ERPs during SPR tasks in which participants saw memory sets of five items and then indicated whether a probe that followed each memory set matched any of the memory set items. Their three SPR tasks consisted of numbers presented visually, numbers presented aurally, or nonverbal stimuli (musical notes) presented aurally. Numbers presented aurally but not visually revealed behavioral and ERP serial position effects. Specifically, probes from recent memory set positions were associated with faster reaction times and larger amplitude P3s than were probes from earlier memory set positions (musical notes demonstrated a similar reaction time effect but no ERP effect). Chao and Knight (1996b) recorded ERPs during a four-item SPR task that used musical notes as stimuli. They found that (a) participants responded more quickly and accurately to recent than to earlier probes and (b) the P3 to recent probes was larger in amplitude and shorter in latency than the P3s to probes from the earlier memory set positions (see also Chao & Knight, 1996a). Although the findings from Patterson et al. (1991) and Chao and Knight (1996b) provide evidence that ERPs to probes in auditory SPR tasks vary according to the serial position of the probe in the preceding memory set, the findings of Patterson et al. (1991) provide no evidence that the same is true for ERPs to probes in visual SPR tasks. Previous research, however, has demonstrated that behavioral recency effects (i.e., accuracy and reaction time) are stronger for auditory than for visual stimuli (e.g., Crowder & Morton, 1969). Patterson et al. (1991) may have failed to find ERP (and behavioral) recency effects in their visual SPR task, therefore, because their experiment lacked the statistical power to detect the smaller recency effects associated with visual stimuli; in fact, they reported that their experiment had relatively low statistical power (Patterson et al., 1991, footnote 2, p. 429). More pervasive and robust recency effects occur when recent items are still in STM and earlier items have been displaced from STM (e.g., see Glazner, 1972). Both Patterson et al. (1991) and Chao and Knight (1996b) used subspan memory sets in which all of the items could be held in STM until the probe was presented. Thus, their experiments

were incapable of examining whether ERPs can reflect the presence versus absence of an item in STM.

The purpose of this study was to examine whether ERPs evoked by probe items in a visual supraspan SPR task vary according to the position of an item in a preceding memory set. To examine this issue, we conducted two experiments. In these experiments, participants engaged in an SPR task that required them to view 12-picture sequences and decide whether a probe picture that followed each sequence was presented in the sequence that immediately preceded the probe. Half of the probes were pictures that were presented in the immediately preceding sequence (match probes), and half were pictures that were not presented in the immediately preceding sequence (nonmatch probes). One third of the match probes were pictures that were presented in the 1st, 2nd, or 3rd position (prime probes) of the preceding sequence, one third were pictures that were presented in the 6th, 7th, or 8th position (middle probes) of the preceding sequence, and one third were pictures that were presented in the 10th, 11th, or 12th position (recent probes) of the preceding sequence.

EXPERIMENT 1

Method

Participants

Nineteen participants (12 women, 7 men) were included in the analyses after data from 9 participants were excluded because of various problems. Data from 3 participants were discarded before data analyses because of technical problems that occurred during data acquisition, data from 5 participants were discarded before data analyses because of excessive physiological artifacts that could not be removed, and data from 1 participant was discarded because the person's accuracy in the behavioral task did not differ significantly from chance. Participants were students in an introductory psychology course at the University of Texas at El Paso; they were participating in partial fulfillment of a course requirement. All participants reported that they were in good health and that they were right handed (mean score of 70 on the Edinburgh Inventory).

Stimuli

The experimental stimuli consisted of 260 computer images of common objects (e.g., fox, doll) from Snodgrass and Vanderwart (1980). This limited number of stimuli necessitated that each image be presented approximately 10 times during the course of the experiment.

Procedure

After arriving at the laboratory, participants were told that the purpose of the experiment was to investigate the electrical brain activity associated with memory. The experimenter explained the procedures involved in recording electroencephalographic (EEG) activity and asked participants to read and sign an informed-consent form. Participants then completed the Edinburgh Inventory to assess hand preference (Oldfield, 1971). Next, the experimenter prepared the participant for EEG recording by attaching the reference, vertical electrooculogram (VEOG), and horizontal electrooculogram (HEOG) electrodes and seating an elastic cap containing the EEG electrodes. Once these preparations were complete, the participant was seated in a comfortable reclining chair approximately 0.5 m in front of the monitor on which the experimental stimuli were displayed. A video camera was used to monitor participants during the experiment.

Before the experiment was initiated, the experimenter reviewed the experimental procedures with the participants. Participants were told that they would see a sequence of 12 pictures depicting common objects and followed, after a short delay, by a probe picture; their task was to carefully view the 12-picture sequence and then indicate, by pressing one of two keys on a keypad, whether the probe was or was not presented in the sequence. The experimenter emphasized that both the accuracy and the speed of their responses were important. Participants also were asked to make match responses (i.e., the probe was in the preceding sequence) with their right thumb and nonmatch responses (i.e., the probe was not in the preceding sequence) with their left thumb. After these instructions, the experimenter initiated the experiment.

Each picture within a 12-item SPR trial was presented for 0.5 s with an interstimulus interval of 0.5 s. A probe picture was presented 1.5 s after the offset of the 12th picture; the probe was presented for 0.5 s. The next sequence began 3.0 s after the offset of the probe picture. Four types of probes were used: (a) pictures located in the 1st, 2nd, or 3rd positions (prime probes) of the preceding sequence, (b) pictures located in the 6th, 7th, or 8th positions (middle probes) of the preceding sequence, (c) pictures located in the 10th, 11th, or 12th positions (recent probes) of the preceding sequence, and (d) pictures that were not presented (nonmatch probe) in the preceding sequence. To equate the number of times that participants indicated that the probe was present versus absent in the preceding sequence, nonmatch probes were presented following 105 sequences, prime probes were presented following 35 sequences, middle probes were presented following 35 sequences, and recent probes were presented following 35 sequences. Thus, a match response was correct for half of the trials, and a nonmatch response was correct for half of the trials. The 210 SPR trials were presented in three sets of 70; there was a 60.0 s break between each set. Three different orderings of the 210 SPR trials were used in the experiment.

Data Acquisition and Reduction

Bioelectrical activity was recorded using ECI Electro-Caps with Ag/AgCl electrodes. EEG activity was recorded from 30 scalp locations and referenced to linked mastoids. VEOG activity was recorded from the right eye by supraorbital and infraorbital electrodes. HEOG activity was recorded by electrodes located outside the outer canthi of the right and left eyes. A ground electrode was located between FPz and Fz electrode locations. The electrodes were filled with a high conductivity gel, and electrical impedance at each recording location was reduced to <5 kohms by abrading with either a blunt needle (scalp locations) or Omni prep (Mastoid, VEOG, & HEOG electrodes). Neuroscan amplifiers were used to amplify, filter (bandpass of DC-30 Hz), and digitize (200 Hz) the bioelectrical signals that were recorded continuously during the experiment.

A number of steps were taken to reduce and quantify the bioelectrical data. First, a regression procedure for removing ocular artifacts from the EEG recordings was applied to the continuous bioelectrical data (Semlitsch, Anderer, Schuster, & Presslich, 1986). Epochs associated with each probe (0.2-s prestimulus, 0.5-s stimulus, and 1.0-s poststimulus periods) were extracted from the continuous data, and the bioelectrical signal at each recording site within each epoch was baseline corrected to the mean of its 0.2-s prestimulus period. Epochs in which EEG activity at any electrode location exceeded ± 70 μV were eliminated. The EEG recordings over each recording site for each participant were then averaged separately for prime, middle, recent, and nonmatch probes that

were correctly identified by the participant. EEG sweeps associated with incorrect responses were not included in ERP waveforms or the subsequent ERP analyses. The ERP waveforms, therefore, included only EEG sweeps that were associated with correct responses and free of physiological artifacts (e.g., eye blinks). The averaged ERP waveforms were then digitally low-pass filtered at 10 Hz.

Before attempting to quantify components of the ERP, we computed and examined grand average waveforms (see Figures 1 and 2). Visual inspection of these waveforms revealed six possible ERP components. We then quantified these six ERP components, at each recording site for each participant and probe type, by selecting the amplitude and latency of the largest deflection (i.e., positive or negative) within a specified latency range around the peak (see Table 1 for latency range and midline site of maximum peak and peak latency at maximum peak). We refer to these potentials according to their polarity and serial order (i.e., first negative, second negative, etc.) but recognize that the potentials observed in this experiment are likely equivalent to potentials that have been observed in other experiments but named differently (e.g., the N3 in the present experiment probably is the N400).

Data Analyses

To investigate the influence of serial position on recognition, we examined (a) the accuracy and reaction time of participants' responses to probe items and (b) the amplitude, latency, and scalp

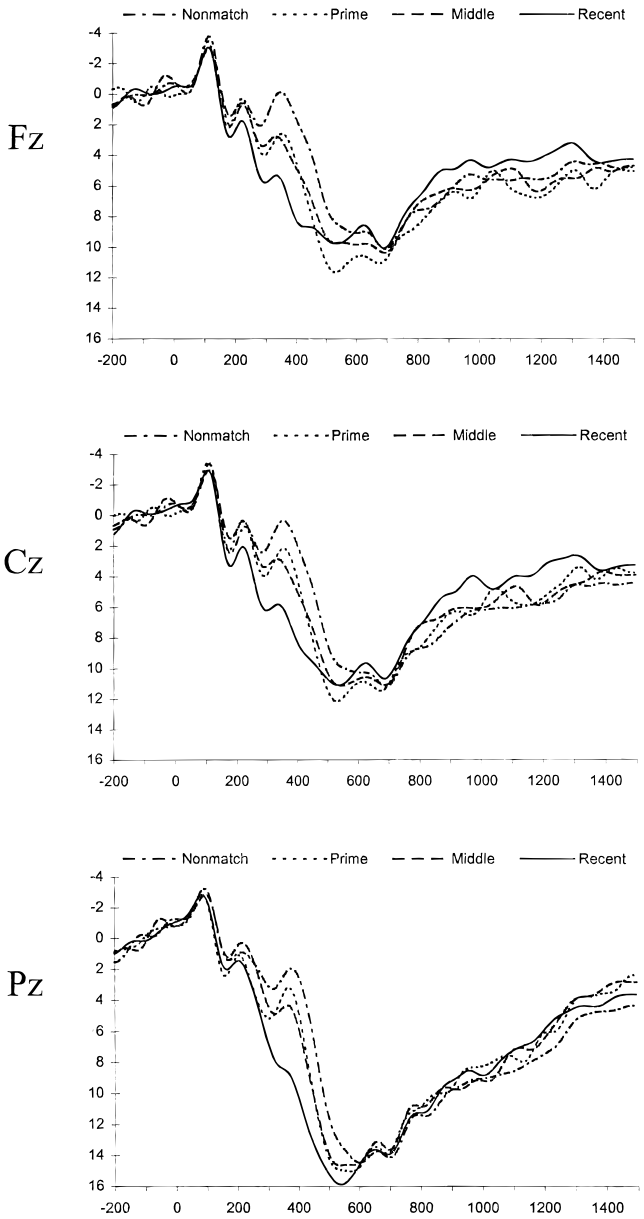

Figure 1. Average waveforms associated with nonmatch, prime, middle, and recent probes at Fz, Cz, and Pz electrode sites in Experiment 1. Positive is plotted down.

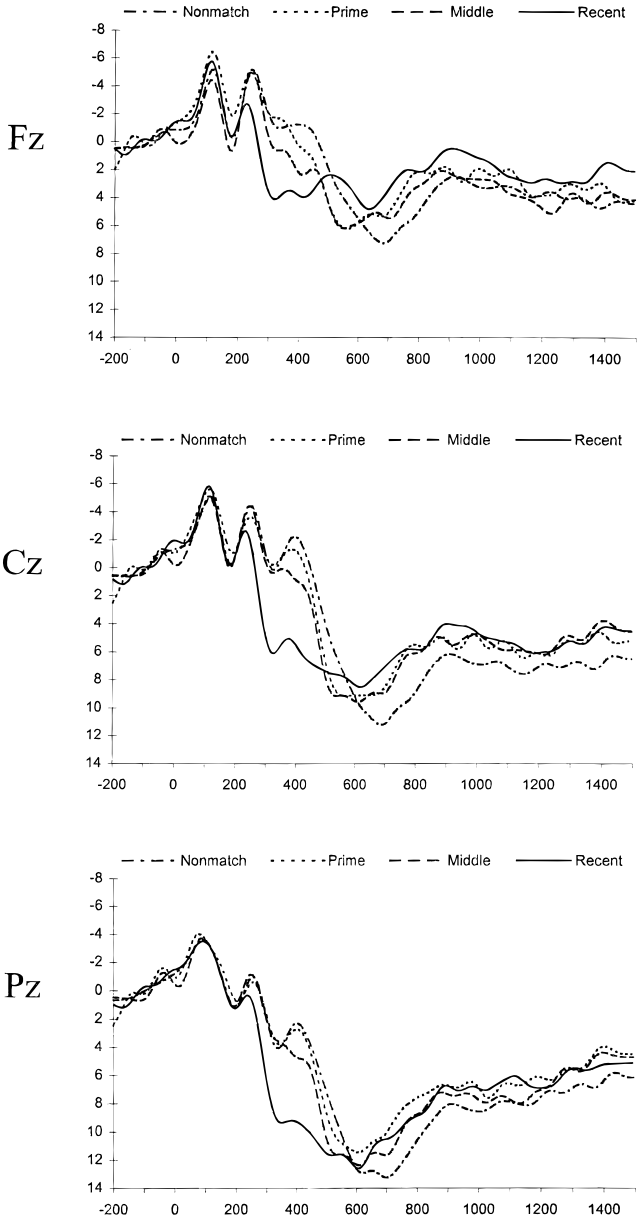

Figure 2. Average waveforms associated with nonmatch, prime, middle, and recent probes at Fz, Cz, and Pz electrode sites in Experiment 2. Positive is plotted down.

Table 1. *ERP Component Characteristics for Experiments 1 and 2*

		Experiment 1		Experiment 2	
Component	Latency range (ms)	Maximum peak	Peak latency (ms)	Maximum peak	Peak latency (ms)
N1	85–115	FCz	105	FCz	108
P1	150–190	Cz	177	Pz	180
N2	195–235	Fz	218	Fz, FCz	223
P2	270–330	Pz	307	Pz	321
N3	335–400	FCz	357	FCz	370
P3	440–700	CPz	593	Pz	619

Table 2. *Response Accuracy and Reaction Time to Probe Stimuli in Experiment 1*

	Accuracy (% correct)		Reaction time (ms)	
Probe	*M*	*SE*	*M*	*SE*
Position				
Prime	76.8	2.7	1,087	36
Middle	73.4	2.7	1,080	33
Recent	85.0	1.9	1,035	33
Type				
Match	78.4	1.9	1,068	33
Nonmatch	82.4	3.2	1,110	41

distribution of the P2, N3, and P3 components to correctly identified probe items.[1] Response accuracy and reaction times were examined using single variable (serial position) multivariate analysis of variance (MANOVAs). The amplitude of each ERP component was examined along the five midline scalp locations using 3 (serial position: probe originally presented in prime, middle, or recent memory set position) × 5 (electrode location: Fz, FCz, Cz, CPz, Pz) MANOVAs. The latency of each ERP component was examined at the scalp location where the component was greatest in amplitude (i.e., most positive for P2 and P3 and most negative for N3, see Table 1) using single variable (serial position) MANOVAs. MANOVAs, as opposed to univariate analyses of variance, were used in all analyses that included an experimental variable with more than two levels to protect against heterogeneity of covariance. Finally, when an omnibus analysis revealed a significant serial position effect, planned contrasts between prime, middle, and recent probes were performed, and the significance of these planned comparisons was assessed using a modified Bonferroni procedure (Keppel, 1982).

To simplify the analyses and presentation of the scalp distribution findings, the scalp distribution of each ERP component was examined over four scalp regions. That is, the scalp distribution analyses included 16 scalp sites that were located over the left frontal (F3, F7, FC3, FT7), left parietal (P3, T5, CP3, TP7), right frontal (F4, F8, FC4, FT8), and right parietal (P4, T6, CP4, TP8) scalp regions. Because differences in the absolute amplitude of ERP components across experimental variables can lead to spurious interactions involving the spatial distribution of ERP components (McCarthy & Wood, 1985), we first eliminated differences in the absolute amplitude of ERP components across experimental variables by standardizing the amplitude values within each experimental variable and subject. This standardization procedure involved computing the mean amplitude and standard deviation of each component across the 16 scalp sites within each experimental condition for each subject. Within each experimental condition and subject, a standardized score (Z score) was then computed at each of the 16 scalp sites by subtracting the mean amplitude and dividing by the standard deviation. These standardized scores were then averaged over the left frontal, left parietal, right frontal, and right parietal scalp regions to form aggregate measures of the activity from these four scalp regions for each ERP component.[2] The scalp distribution of each component was then examined using 3 (serial position) × 2 (lateral: left vs. right) × 2 (sagittal: frontal vs. parietal) MANOVAs on these averaged standardized scores.[3]

[1] As anticipated, preliminary analyses revealed that serial position did not influence the early ERP components (i.e., N1, P1, and N2). These three potentials, therefore, will not be discussed further.

Results

Behavioral responses

Overall participants accuracy was high; probes were correctly identified 80% of the time. Both accuracy and reaction time differed for the three probe positions, $F(2,17) = 10.4$, $p = .001$ and $F(2,17) = 7.3$, $p = .005$, respectively (Table 2, left). Follow-up analyses revealed that (a) participants were more accurate and quicker in response to recent probes than they were to either prime or middle probes and (b) responses to prime and middle probes differed neither in accuracy nor reaction time. Thus, both accuracy and reaction time analyses revealed a recency but not a primacy effect.

ERP Waveforms

P2 component. The average waveforms shown in Figure 1 indicate an early dissociation of probes by serial position that is statistically reliable at P2, $F(2,17) = 7.9$, $p = .004$. Planned comparisons revealed that (a) the P2 evoked by recent probes ($M = 7.8\ \mu$V, $SE = 1.5\ \mu$V) was larger in amplitude than the P2s evoked by either prime probes ($M = 5.5\ \mu$V, $SE = 1.5\ \mu$V) or

[2] We opted for this rather conservative approach in which data from multiple scalp sites were aggregated into scalp regions for three reasons. First, data from participants who had missing data at a scalp site could be included in the analyses because the missing data could be replaced with the mean of other sites in the scalp region. Second, there are no well-established techniques for statistically comparing activity from numerous (e.g., >20) scalp locations. Third, aggregating data across electrode locations should help protect against spurious, unreliable effects associated with making numerous comparisons (i.e., if every scalp site were considered separately in the analyses). Aggregating scalp sites, however, will limit spatial sensitivity and may potentially obscure significant effects.

[3] Standardizing the amplitude of ERP components eliminates absolute differences in the amplitude of the components across experimental variables. Analyses of standardized amplitudes are, therefore, only sensitive to differences in the scalp distribution of the ERP components across experimental variables and not to differences in the absolute amplitude of the components across experimental variables. Similar analyses of the raw (i.e., unstandardized) amplitude scores revealed (a) scalp distribution findings essentially identical to those reported here and (b) the same support for the experimental hypotheses as found in the analyses of the midline sites.

middle probes ($M = 5.5\ \mu V$, $SE = 1.8\ \mu V$) and (b) there was no significant amplitude difference between the P2s evoked by prime and by middle probes.

The analysis of P2 latency revealed a significant serial position effect, $F(2,17) = 4.5$, $p = .026$. In contrast to the reaction time data shown in Table 2, the P2 evoked by recent probes ($M = 319$ ms, $SE = 3.9$ ms) had the longest latency, followed by the P2s evoked by middle probes ($M = 310$ ms, $SE = 4.9$ ms) and prime probes ($M = 301$ ms, $SE = 5.3$ ms). However, recent probes evoked an ERP with a large P2 and essentially no N3 (Figure 1). Thus, this significant latency effect most likely does not reflect the latency of the cognitive/neural processes that produce the P2 but is caused by an overlap between the P2 and P3 components (because of the lack of an N3 for recent probes).

The scalp distribution analysis revealed that the P2 was maximally positive over the parietal and right scalp regions and that the amplitude difference between the frontal and parietal areas was larger over the right scalp regions. Stimulus position, however, did not interact with either the sagittal or lateral variables.

N3 component. The ERP dissociation of recent probes from prime and middle probes continued into the N3 component, $F(2,17) = 21.6$, $p < .001$ (Figure 1). As was found for the P2, the amplitude of the N3 evoked by recent probes ($M = 5.8\ \mu V$, $SE = 1.3\ \mu V$) differed significantly from those evoked by prime ($M = 1.4\ \mu V$, $SE = 1.5\ \mu V$) and middle ($M = 1.8\ \mu V$, $SE = 1.6\ \mu V$) probes, which did not differ significantly. The analysis of N3 latency revealed no significant serial position effect.

The analysis of the scalp distribution revealed that the N3 was maximally negative over the frontal and left scalp regions. Thus, its scalp distribution was similar to that of the P2 in that it was more positive over the parietal and right scalp regions. Stimulus position did not interact with either the sagittal or lateral variables.

P3 Component. Unlike the P2 and N3 components, the serial position of a stimulus did not affect the amplitude of the P3 (see Figure 1). The only significant effect was a sagittal main effect, $F(4,15) = 14.2$, $p < .001$, as the amplitude of the P3 varied across the midline of the scalp ($M_{Fz} = 13.4\ \mu V$; $M_{FCz} = 14.8\ \mu V$; $M_{Cz} = 14.4\ \mu V$; $M_{CPz} = 17.9\ \mu V$; $M_{Pz} = 17.3\ \mu V$). The analysis of P3 latency revealed no significant serial position effect.

The scalp distribution analysis showed that the P3 was maximally positive over the parietal and right scalp regions. Stimulus position did not interact with either the sagittal or lateral variables.

Discussion

The objective of this experiment was to examine whether ERPs evoked by correctly recognized probe items vary according to the position of the probe in a preceding 12-item memory set. Behavioral evidence revealed strong support for a recency effect; participants were more accurate at identifying and responded more quickly to probes that were in the 10th, 11th, or 12th memory set positions. Comparable evidence for a recency effect was also observed in the ERPs; amplitude differences between the ERPs evoked by recent probes, compared with prime and middle probes, began as early as 300 ms after the probe was presented and lasted for at least 100 ms, extending over the P2 and N3 components of the ERP. The ERPs revealed no consistent evidence, however, that the speed or latency of the cognitive processes reflected in the ERP components is influenced by serial position (i.e., nonsignificant latency effects) or that different sets of neural units are activated by prime, middle, or recent probes (i.e., because the scalp distribution of the components was not influenced by the serial position of the probe).

EXPERIMENT 2

A principle difference between the ERPs evoked in Experiment 1 and ERPs evoked in other memory tasks is the presence of a P2 component that peaked around 300 ms. Previous research examining ERPs during memory tasks has focused on two components of the ERP: an N4 that peaks around 400 ms, which is likely analogous to the component we refer to as the N3, and a P3 that peaks around 600 ms (for reviews, see Kutas, 1988; Rugg, 1995). The ERP waveforms elicited by probes contained three distinct peaks (i.e., P2, N3, P3); thus, each of these components was examined by quantifying their peak amplitude. Previous research has tended to quantify the N4 as the average amplitude from approximately 250 to 400 ms and the P3 as the average amplitude from approximately 400 to 600 ms. Thus, although previous research has not explicitly quantified the P2 component, it is within the latency range that is typically used to quantify the N4. In fact, a P2 does appear to be present in the ERP waveforms from some previous research (e.g., Barrett et al., 1988; Berman et al. 1991; Pratt et al., 1989; Rugg & Nagy, 1989), although it is not as large as the P2 observed in the present experiment.

To assess the robustness of these results, particularly those involving the P2 component, we conducted a second experiment. A potential limitation with Experiment 1 was that each stimulus had to be used multiple times as a memory set item. Although ERP research explicitly examining STM has included use of stimuli multiple times as memory set items (e.g., Chao & Knight, 1996b; Patterson et al., 1991), in ERP research examining other memory phenomena stimuli have been used only once as memory set items (e.g., Berman et al., 1991; Friedman, 1990a, 1990b). Although we did not systematically query participants in Experiment 1, several participants volunteered that a demanding aspect of the task was deciding whether the probe had occurred in the most recent memory set or in earlier memory sets. Temporal confusion as to which memory set a probe belonged would most likely be greater for prime and middle memory set items than for recent items because prime and middle stimuli are temporally closer to earlier memory sets, which could lead to more intermemory set confusions for the prime and middle probes than for recent probes. Thus, proactive interference from earlier memory sets may have influenced the behavioral and ERP data observed in Experiment 1. To examine these issues, we conceptually replicated Experiment 1 using a large number of stimuli so each stimulus only had to be used once as a memory set item.

Method

Participants

Sixteen participants (9 women, 7 men) were included in the analyses after data from 9 participants were excluded because of various problems.[4] Data from 5 participants were discarded before data analyses because of technical problems that occurred during data acquisition, and data from 4 participants were discarded before

[4]For one of the participants included in the analyses, there were no data for one midline scalp site (FCz). Therefore, analyses and results in which the midline scalp sites are an experimental variable include data from only 15 participants.

data analyses because of excessive physiological artifacts that could not be removed. As in Experiment 1, participants were students in an introductory psychology course, and all reported that they were in good health and that they were right handed (mean score of 79 on the Edinburgh Inventory).

Stimuli

The experimental stimuli consisted of 2,625 clip art images of common objects (Task Force Clip Art). This number of stimuli allowed for each image to be presented only once during the course of the experiment as a memory set item. The difference between the number of stimuli (260 in Experiment 1 and 2,625 in Experiment 2) is the only significant methodological difference between the two experiments.

Procedure

Other than the following exception, the experimental procedures were identical to those used in Experiment 1. Rather than using three different orderings of the 210 SPR trials (i.e., as was done in Experiment 1), a different, randomly generated series of 210 SPR trials was used for every subject. That is, the stimuli in each 12-item SPR trial and the order of the 210 SPR trials were randomly determined for each subject.

Data Acquisition and Reduction

The data acquisition and reduction procedures were identical to those used in Experiment 1.

Results

Behavioral Responses

The findings were identical to those of Experiment 1: (a) participants were very accurate at identifying probes (81% correct) and (b) a recency but no primacy effect was obtained (cf. Tables 2 and 3). As shown in Table 3, the serial position of the probe influenced both accuracy and reaction time, $F(2,14) = 11.7$, $p = .001$ and $F(2,14) = 7.5$, $p = .006$, respectively. As in Experiment 1, follow-up analyses revealed that (a) participants were more accurate and quicker in response to recent probes than they were to either prime or middle probes and (b) responses to prime and middle probes did not differ in either accuracy or reaction time.

ERP Waveforms

P2 component. Consistent with the findings of Experiment 1, the average waveforms shown in Figure 2 indicate an early dissociation of probes by serial position that is statistically reliable at P2, $F(2,13) = 7.1$, $p = .008$. As in Experiment 1, follow-up analyses revealed that (a) the P2 evoked by recent probes ($M = 7.1\ \mu$V, $SE = 1.1\ \mu$V) was larger in amplitude than the P2s evoked by either prime probes ($M = 1.3\ \mu$V, $SE = 1.1\ \mu$V) or middle probes ($M = 1.9\ \mu$V, $SE = 1.5\ \mu$V) and (b) there was no significant amplitude difference between the P2s evoked by prime and middle probes.

The analysis of P2 latency revealed a significant serial position effect; the P2 evoked by recent probes ($M = 326$ ms, $SE = 2.7$ ms) had the longest latency, followed by the P2s evoked by middle probes ($M = 318$ ms, $SE = 4.7$ ms) and prime probes ($M = 312$ ms, $SE = 5.8$ ms), $F(2,14) = 7.3$, $p = .007$. As in Experiment 1, this effect probably was due to the overlap between the P2 and P3 components for recent probes (see Figure 2) and thus does not reflect the latency of the cognitive/neural processes that produce the P2.

The scalp distribution analysis revealed that the P2 was maximally positive over the parietal scalp regions and that the amplitude difference between the frontal and parietal areas was larger over the right scalp regions. As in Experiment 1, stimulus position did not interact with either the sagittal or lateral variables.

N3 component. As in Experiment 1, the dissociation of recent probes from prime and middle probes continued into the N3 component, $F(2,13) = 8.7$, $p = .004$ (see Figure 2). Planned comparisons revealed that the amplitude of the N3 evoked by recent probes ($M = 4.0\ \mu$V, $SE = 1.3\ \mu$V) differed significantly from those evoked by prime ($M = -1.9\ \mu$V, $SE = 1.2\ \mu$V) and middle ($M = -0.4\ \mu$V, $SE = 1.5\ \mu$V) probes, which did not differ significantly. The analysis also revealed a significant sagittal main effect as the amplitude of the N3 varied across the midline of the scalp ($M_{Fz} = -0.9\ \mu$V; $M_{FCz} = -1.2\ \mu$V; $M_{Cz} = -0.4\ \mu$V; $M_{CPz} = 1.4\ \mu$V; $M_{Pz} = 3.9\ \mu$V), $F(4,11) = 4.4$, $p = .024$. Although this sagittal effect was not significant in Experiment 1, the midline scalp distribution of the N3 in both experiments was identical (i.e., generally becoming more negative from parietal to frontal sites with minimal amplitude at FCz). As in Experiment 1, the analysis of N3 latency revealed no significant serial position effect.

The scalp distribution analyses revealed a significant Serial Position × Lateral interaction, $F(2,14) = 3.8$, $p = .047$. This interaction occurred because recent and prime probes evoked an N3 that was nominally more negative over the left scalp regions, whereas middle probes evoked an N3 that was nominally more negative over the right scalp regions. Because a similar pattern was not observed in Experiment 1, we are skeptical about the robustness of this interaction and thus will not discuss it further. As in Experiment 1, the amplitude of the N3 was maximally negative over the frontal scalp regions.

P3 component. The analysis of peak amplitude revealed results identical to those found in Experiment 1. First, unlike the P2 and N3 components in both experiments, the serial position of a stimulus did not affect the amplitude of the P3 (compare Figures 1 and 2). Second, there was a significant sagittal main effect, $F(4,11) = 6.1$, $p = .008$, as the amplitude of the P3 varied across the midline of the scalp ($M_{Fz} = 7.9\ \mu$V; $M_{FCz} = 9.4\ \mu$V; $M_{Cz} = 11.7\ \mu$V; $M_{CPz} = 13.5\ \mu$V; $M_{Pz} = 14.4\ \mu$V).

Unlike Experiment 1 but in agreement with the reaction time data of Table 3, the analysis of P3 latency revealed that the P3 evoked by recent probes had the shortest latency, followed by

Table 3. *Response Accuracy and Reaction Time (ms) to Probe Stimuli in Experiment 2*

	Accuracy (% correct)		Reaction time (ms)	
Probe	*M*	*SE*	*M*	*SE*
Position				
Prime	78.6	3.2	1,077	43
Middle	72.0	4.1	1,094	36
Recent	88.6	1.6	995	44
Type				
Match	79.7	2.5	1,055	39
Nonmatch	82.8	2.6	1,071	44

prime probes and middle probes, $F(2,14) = 5.6$, $p = .016$. Post hoc comparisons revealed that the latency of the P3 evoked by recent probes ($M = 555$ ms, $SE = 19.8$ ms) was significantly shorter than the latencies of the P3s evoked by prime ($M = 604$ ms, $SE = 15.6$ ms) and middle ($M = 614$ ms, $SE = 18.4$ ms) probes, which did not differ significantly. Although this serial position effect was not significant in Experiment 1, the pattern of means in both experiments was identical.

The scalp distribution analysis revealed a significant Serial Position × Sagittal interaction, $F(2,14) = 5.9$, $p = .014$ (Figure 3). Visual inspection of Figure 3 suggests that this interaction was due to the larger difference between the parietal and frontal scalp regions for recent than for prime and middle probes. This significant Serial Position × Sagittal interaction implies that the set of neural units associated with a recent probe may differ from the set associated with prime and middle probes (e.g., see Johnson, 1993). The pattern of data depicted in Figure 3 was also observed in Experiment 1, but the Serial Position × Sagittal interaction was not significant in Experiment 1. As in Experiment 1, the amplitude of the P3 was maximally positive over the parietal scalp regions.

Discussion

The findings of this experiment provide converging evidence with those of Experiment 1 regarding the recency effect. As in Experiment 1, participants were more accurate at identifying and responded more quickly to recent probes; recent probes, compared with prime and middle probes, evoked more positive P2 and N3 components of the ERP. In addition, two other findings, which displayed similar patterns in Experiment 1 but were not significant, emerged in this experiment. First, recent probes evoked a shorter latency P3 than did prime and middle probes. Given that the P3 is not influenced by factors that selectively influence response processes (e.g., Crites, Cacioppo, Gardner, & Berntson, 1995; Magliero, Bashore, Coles, & Donchin, 1984), this finding implies that cognitive processes that occur before response selection and execution are partially responsible for the behavioral advantage that allows people to more quickly identify recent probes. Second, the serial position of a probe in a preceding memory set influenced the sagittal scalp distribution of the P3, suggesting that different neural units are involved with processing prime, middle, and recent probes.

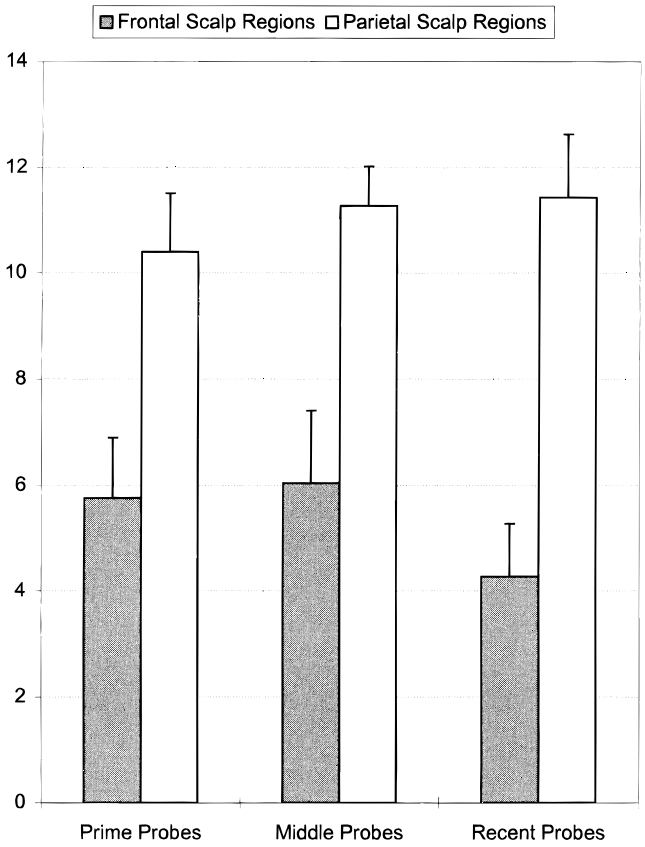

Figure 3. Peak amplitude of P3 over frontal and parietal scalp regions for prime, middle, and recent probes in Experiment 2.

The only significant methodological difference between the two experiments was the number of times participants saw each stimulus during the course of the experiment. In Experiment 1, participants saw each stimulus approximately 10 times as a memory set item, whereas participants in Experiment 2 saw each stimulus only once as a memory set item. Thus, participants in Experiment 1, compared with those in Experiment 2, may have experienced interference when judging whether a probe matched or did not match an item in the immediately preceding memory set (i.e., because they had to determine whether the probe was in the immediately preceding memory set or an earlier one). Although the similarities in the ERPs and the behavioral responses suggest that the cognitive processes underlying the memory judgments in the two experiments were largely similar, there may be subtle differences that are not readily apparent. To examine this issue, we conducted a series of analyses that included data from both experiments and that treated experiment (i.e., 1 vs. 2) as a between-subjects variable.

The findings from these combined analyses mirrored, for the most part, those from the separate analyses (i.e., analyses reported in the results sections), but there were two differences between the ERPs evoked in each experiment. First, the amplitudes of the P2, N3, and P3 components were more positive over the right than the left scalp regions in Experiment 1 and more symmetrically distributed over the right and left scalp regions in Experiment 2.[5] Second, the P3 evoked in Experiment 1 was larger than that evoked in Experiment 2. This finding might be a function of the same cognitive process that gives rise to old/new effects from approximately 400 to 600 ms (i.e., P3 evoked by old stimuli is larger than P3 evoked by new stimuli) in previous research (e.g., Rugg & Nagy, 1989). That is, the stimuli in Experiment 1, which were used approximately 10 times during the course of the experiment, may evoke a more positive P3 because they were relatively old compared to those in Experiment 2, which were used only once (for nonmatch probes) or twice (for match probes). Alternatively, research on recognition memory also suggests that people may indicate that they recognize a stimulus because they (a) explicitly recall the episode in which they encountered the stimulus (recol-

[5] Although this significant effect may be due to a theoretically interesting variable (e.g., proactive interference), it may also be a function of differential data loss at the lateral electrodes in the two experiments. That is, the aggregate scalp region data were obtained by averaging data from each of the four electrode sites within each scalp region; if one of these electrode sites was missing, it was replaced with the mean of the remaining sites (see Footnote 2). Unfortunately, more electrode sites over the right scalp regions were missing in Experiment 1 than in Experiment 2. Thus, the lateral effects in Experiment 1 and the differential lateral effects between the two experiments may be due to these missing data.

lection) or (b) have a familiarity with the stimulus (familiarity) but cannot recall the specific episode in which they encountered the stimulus (e.g., Jacoby & Kelley, 1992; Mandler, 1991). Because stimuli in Experiment 2 were used only once whereas stimuli in Experiment 1 were used multiple times during the course of the experiment, participants in Experiment 2, relative to those in Experiment 1, may have relied more on familiarity and less on recollection. Rugg (1995) recently suggested that the amplitude of the P3 may reflect recollection. Thus, the larger P3 in Experiment 1 may reflect greater use of recollection in this experiment relative to Experiment 2.

GENERAL DISCUSSION

In spite of significant advancements in our understanding of memory, the cognitive processes that give rise to primacy and especially recency effects remain a source of contention among researchers. In these experiments, we examined ERPs evoked by probe items in a visual supraspan SPR task with the hope that ERPs would provide a means of investigating the cognitive mechanisms that underlie primacy and recency. The findings of these experiments clearly demonstrate that ERPs evoked when a visual probe is correctly recognized differ according to the item's serial position in a preceding memory set. More specifically, our results revealed that ERPs associated with the correct recognition of stimuli presented originally in recent (recent probe) memory set positions are more positive from approximately 300 to 400 ms than are ERPs associated with the correct recognition of stimuli presented originally in prime (prime probe) and middle (middle probe) memory set positions. Furthermore, this enhanced positivity to recent probes spanned two components of the ERP: a P2 that peaked approximately 315 ms after stimulus presentation and an N3 that peaked approximately 365 ms after stimulus presentation.

Our findings extend previous research by demonstrating that recent visual probes evoke more positive ERPs than do prime and middle visual probes. That is, previous research has demonstrated that recent probes in SPR tasks using verbal auditory (Patterson et al., 1991) and nonverbal auditory (Chao & Knight, 1996b) stimuli evoke more positive ERPs than do prime and middle probes, but this previous research provided no evidence that the same was true for visual stimuli (Patterson et al., 1991). One important difference between our findings and those of Patterson et al. and Chao and Knight, however, concerns the component(s) of the ERP that differentiate recent from earlier probes. Patterson et al. and Chao and Knight found ERP differences in the P3 component of the ERP, whereas our experiments revealed ERP differences in two earlier components, the P2 and N3, and no significant differences in the P3 component.

There are at least three significant differences between our experiments and the earlier research that may account for these different results. First, the experiments used different types of stimuli and presented these stimuli in different modalities. That is, we used visually presented pictures, Chao and Knight (1996b) used aurally presented musical notes; and Patterson et al. (1991) used visually and aurally presented numbers and aurally presented musical notes (but found ERP effects only for aurally presented numbers). Previous research has demonstrated superior recognition memory for pictures than for other stimuli (e.g., Standing, Conezio, & Haber, 1970); thus some of the cognitive processes that underlie memory for pictures may differ from those involved in memory for other types of stimuli. Second, we defined recent probes as probes initially presented in one of the last three memory set positions, whereas Patterson et al. and Chao and Knight defined recent probes as probes initially presented in the last memory set position. Thus, our findings indicate that probes originally presented in memory set positions 10–12 differ from those presented originally in memory set positions 1–3 and 6–8. Alternatively, Patterson et al. and Chao and Knight demonstrated that probes originally presented in the last memory set position (Positions 5 or 4, respectively) differed from those presented originally in earlier positions (e.g., Positions 1–3). The amplitude of the P3 may be influenced by short-term recency (i.e., differences between last and next to last item), and the earlier ERP components may be influenced by long-term recency, which would explain why Patterson et al. and Chao and Knight found P3 differences whereas we found differences in the P2 and N3 components of the ERP.

The third experimental difference that could account for the different findings concerns the type of SPR tasks used in the experiments. Chao and Knight (1996b) and Patterson et al. (1991) used subspan SPR tasks (4- and 5-item memory sets, respectively) in which all of the memory set items could be held within STM until a decision was made concerning the probe, whereas we used supraspan SPR tasks (12-item memory sets) in which the memory sets contained more stimuli than could be held in STM. Supraspan and subspan SPR tasks may require different cognitive processes (e.g., see Burrows & Okada, 1975) that may, at least partially, be reflected in the ERPs to probe items. For example, when participants know they will only see subspan SPR tasks, as was the case in the studies of Patterson et al. and Chao and Knight, they can simply store memory set items in STM and then search STM for the probe item. Supraspan SPR tasks, however, require a different memory strategy. Participants might try to commit all of the items to long-term memory (LTM), which could eliminate the influence of STM if the cognitive processes involved in moving items to LTM requires STM capacity. Thus, our ERP results may reflect the activity of LTM processes, and the ERP findings from subspan SPR tasks may reflect the activity of STM processes. Alternatively, if participants know the number of stimuli in each memory set, as was the case in our experiments, they might try to commit the early items to LTM and then hold the last couple of items in STM. If STM and LTM are separate memory systems that require different encoding and retrieval processes, this memory strategy would require participants to change encoding processes during the memory set and then use two different memory retrieval processes. Thus, the differences between our findings and previous research could be caused by a number of experimental differences. More research will be needed to address these issues.

The principal advance of these experiments over previous research is the finding that the P2 and N3 components of the ERP evoked by stimuli seen very recently and likely to still be in STM differ from those evoked by stimuli seen slightly less recently and likely to no longer be in STM. Experiments using continuous recognition tasks have demonstrated that ERPs evoked by "old" stimuli are more positive from approximately 250 to 600 ms than are ERPs evoked by "new" stimuli (for a review, see Rugg, 1995). Findings have revealed that the number of items that intervene between the first and second instance of the stimulus do not influence the magnitude of these old/new ERP differences regardless of whether the intervening items displace the first instance of the stimulus from STM or not (Berman et al., 1991; Friedman, 1990a, 1990b). Thus, research using the continuous recognition paradigm suggests that ERPs to items in STM do not differ from ERPs to items recently displaced from STM, whereas our results using a supraspan SPR task suggest that items in STM and items

recently displaced from STM do evoke different ERPs. These different findings suggest that the cognitive and neural processes that give rise to ERPs in SPR and continuous recognition tasks are not synonymous. As suggested above, one potentially important difference between the two tasks is the dual nature of the continuous recognition task as compared with the SPR task (i.e., stimuli in continuous recognition tasks may initiate encoding and retrieval processes, whereas probes in SPR tasks may initiate only retrieval processes).

Two conceptualizations of short-term memory are prevalent in the literature (Cowan, 1993). One conceptualization regards STM as a distinct memory store (or stores) that holds items that are currently the focus of attention (e.g., Atkinson & Shiffrin, 1968; Baddeley, 1986; Raaijmakers & Shiffrin, 1981). In general, this conceptualization of memory assumes that items enter into a short-term memory store, which has limited capacity and duration, and then are either (a) actively held in STM and/or transferred to a long-term store or (b) displaced by new information. One cause of the recency effect is the presence of items in this short-term store at the time of the memory test. Thus, the presence of recent items in a short-term store might account for the more positive P2 and N3 components of the ERP to recent, as compared with prime and middle, probes in the present experiments. However, one difficulty with this interpretation is the failure to find similar ERP effects in continuous memory paradigms. Furthermore, Figures 1 and 2 suggest that the P2 and N3 components in the ERPs evoked by prime and middle probes are more positive than those evoked by nonmatch probes. To assess whether these differences were significant, ancillary analyses were performed comparing the P2s and N3s evoked by prime and middle probes with those evoked by nonmatch probes; these analyses revealed that prime and middle probes evoked more positive P2s and N3s than did nonmatch probes. The present results, therefore, demonstrate that the amplitudes of the P2 and N3 to recent probes are more positive than are those to prime and middle probes and that the amplitudes of these ERP components to prime and middle probes are more positive than are those to nonmatch probes. Thus, this conceptualization of STM, which generally regards items as either present or absent from STM, does not match well with the present ERP results, which suggest gradients of activity.

A second conceptualization of STM regards it as a subset of long-term memory that is in an activated state (e.g., Cowan, 1988; Potter, 1993; see also Ericsson & Kintsch, 1995). One useful feature of this conceptualization is that activation can be viewed along a continuum. Cowan (1988), in fact, postulated that STM reflects only a subset of the elements in LTM that are currently in an activated state, the subset that is the current focus of attention. Thus, exposure to a stimulus may put relevant elements in LTM into a high state of activation that decreases gradually over time; recency would then result because highly activated stimuli would be easier to recall (e.g., see Baddeley & Hitch, 1993). This conceptualization of memory fits well with the assumptions that underlie ERPs and also with the results of these experiments. That is, the amplitude of ERP components is assumed to reflect the degree of activation of cognitive/neural processes. In the present experiments, therefore, the ERP amplitude gradient from recent probes to prime and middle probes to nonmatch probes could be attributed to the activation of elements in LTM. Cowan's conceptualization of memory would hold that recent probes have the most positive ERPs because these memory traces in LTM are active and the focus of current attention, whereas prime and middle probes have ERPs that are more positive than nonmatch probes because these memory traces are still active but are not the focus of current attention. This conceptualization of memory also fits well with previous research that has demonstrated that old/new ERP differences occur in memory and nonmemory (e.g., priming) tasks (for reviews, see Kutas, 1988; Rugg, 1995).

Although we have suggested that the findings of these experiments fit more closely with the notion of STM as an activation of elements in LTM than as a distinct memory store (or stores) separate from LTM, these experiments are by no means definitive. The modal model of memory, which conceptualizes STM as a separate store, has been very enduring, and its conceptualization of STM can easily be adjusted to account for the present findings (i.e., by incorporating the ideas of decay and activation). Furthermore, activation models of memory may work well for memory of familiar material but not for memory of unfamiliar material (i.e., items that are not in LTM). One potentially useful approach is to assume that there are two distinct memory systems: one that relies on the activation of elements in LTM and another separate store that can be used for unfamiliar material (e.g., Potter, 1993). Research using ERPs may be useful for examining these issues. For example, if there are multiple memory systems, ERPs evoked in SPR tasks using pictures that depict familiar and namable items, such as those used in our experiment, might differ from ERPs evoked in SPR tasks using unfamiliar and unnamable items. Rugg and Nagy (1987) reported some evidence that old/new ERP repetition effects differ depending on the ability of a stimulus to access and activate lexical memory.

The hallmark characteristic of the serial position effect is that items near the beginning and end of a memory set are more likely to be recalled or recognized. In the present experiments, however, the only serial position effect to emerge was a recency effect; response accuracy was greater for probes that were in the recent memory set positions than for probes in the prime memory set positions. In retrospect, this finding is not surprising given research demonstrating that primacy and recency depend on the interstimulus interval and the delay between the last stimulus and the probe (e.g., Neath, 1993; Wright et al., 1985). The relatively short interstimulus interval and short delay between the last stimulus and probe in our experiments should have produced a recency effect. Given that there are no memorial advantages for stimuli presented originally in the prime memory set positions, it is not surprising that the ERP evoked by the probes presented originally in the prime and middle memory set positions are comparable.

In these experiments, we examined two potentials of the ERP that varied according to the serial position of a probe in a preceding memory set. Given the similarity in the behavior of the P2 and the N3, one might argue that there is a single cognitive/neural process responsible for the results of these experiments. That is, serial position may not influence the P2 and N3 but may influence another ERP component that temporally overlaps the P2 and N3 components. We have no definitive evidence to determine whether the present results reflect the activity of two processes or a single process. To establish that there are two cognitive/neural processes, experimental factors that can differentially influence the amplitude of the P2 and N3 components must be demonstrated. To investigate this issue further, therefore, future research should quantify both the P2 and N3 and not simply examine the average amplitude over this latency range.

Serial position effects have been a focus of research in psychology for over 100 years, and there is still no universally (or even widely) accepted account for these effects. Although these experiments offer no definitive solutions, they do provide some

interesting findings and point to some potentially useful steps for future investigations of memory and serial position effects. First, they demonstrate that ERPs differ according to the position of a stimulus in a preceding memory set and thus offer the possibility that research using ERPs can help identify the cognitive and neural processes that underlie serial position effects. Second, the differences and similarities between the ERPs evoked in this SPR task and the ERPs evoked in other memory tasks should provide fertile ground for using ERPs to investigate memory. Third, because SPR tasks can be used in other species (e.g., Sands & Wright, 1980; Wright et al., 1985), the findings of these experiments may provide a basis for comparative (i.e., across species) ERP research.

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