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## Event-related potential correlates of the serial position effect in short-term memory <sup>1</sup>

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**Summary** Event-related potential (ERP) correlates of the serial position effect in short-term memory were investigated using a memory scanning task. Nine normal young adults (18–39 years) indicated whether a probe item was a member of a previously presented 5-item memory set by pressing 1 of 2 reaction-time buttons. Three types of stimuli were used: verbal digits presented both auditorily and visually, and musical notes presented auditorily. The ERPs to the probes were separately averaged according to the serial position of the probe (1, 2, 3, 4 or 5) in the memory set. The ERPs to the memory set items in positions 1, 3 and 5 also were separately averaged.

Both baseline-to-peak and average amplitudes of a late positive parietal potential to the probes were larger to probe items presented in the last position in the memory set than to probes presented in the middle positions (2, 3 and 4), showing a significant recency effect, but only for auditory digits. Reaction time reflected significant recency effects for both auditory digits and notes, but not for visual digits. Response accuracy (percent correct) showed a significant recency effect only for notes. For each stimulus type, both the baseline-to-peak and average amplitudes of a late frontal component to the memory set items became more negative (in the case of the visual digits, less positive) in the third and last serial position of the memory set compared to the first. These findings provide electrophysiological evidence of serial position effects in short-term memory, which, during memory scanning, are dependent on stimulus modality (auditory, visual) and type (verbal, non-verbal).

**Key words:** Serial position effects; Event-related potentials; Short-term memory

A number of studies have used a task originally proposed by Sternberg (1966, 1969, 1975) to investigate how scanning in short-term memory is reflected in event-related potentials (ERPs) (Marsh 1975; Roth et al. 1975; Gomer et al. 1976; Adam and Collins 1978; Ford et al. 1979; Pfefferbaum et al. 1980; Gaillard and Lawson 1984; Starr and Barrett 1987; Pratt et al. 1989a, b, c). In the memory scanning task, individuals are presented with a short list of items (the memory set), followed by a probe item, and they are asked to decide by pressing a reaction time (RT) button whether the probe item was or was not a member of the memory set. Sternberg (1966, 1969) and others (e.g., Burrows and Okada 1971, 1973; Anders et al. 1972; Cavanagh 1972; Wingfield 1973) observed that increasing the number of items in the memory set prolonged RTs to the probes in a systematic manner. Sternberg (1966, 1969, 1975) maintained that memory scanning in this task was serial and exhaustive since RTs increased

linearly with set size, and since the slope of the RT/set size function did not differ between in-set (positive) and out-of-set (negative) probes, indicating that subjects were scanning the entire list before making a decision.

When ERPs are collected in the memory scanning task, the probe is associated with a high amplitude sustained late positive potential (e.g., Gomer et al. 1976; Adam and Collins 1978; Ford et al. 1979; Pfefferbaum et al. 1980; Pratt et al. 1989a, b). The memory set items also elicit a sustained potential, the polarity and scalp distribution of which varies with stimulus modality (auditory, visual) and type (verbal, non-verbal) (Pratt et al. 1989c). In agreement with the findings using RT, several studies have observed a linear increase in the latency of the late positive component to the probes as memory set size is increased (Marsh 1975; Gomer et al. 1976; Adam and Collins 1978; Ford et al. 1979; Starr and Barrett 1987; Pratt et al. 1989a, b), with variable effects on amplitude (Marsh 1975; Roth et al. 1975; Gomer et al. 1976; Gaillard and Lawson 1984; Pratt et al. 1989a, b).

In contrast to these findings, however, there is other evidence indicating that the serial exhaustive scanning hypothesis may not be appropriate, and that alternative models, such as those emphasizing parallel processing, trace strength, or a self-terminating search may be more relevant (Wickelgren and Norman 1966; Burrows and

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Okada 1971; Kirsner and Craik 1971; Baddeley and Ecob 1973; Corballis et al. 1972; Cavanagh 1976; Ratcliff 1978; Corballis 1979; Hacker 1980; Hockley and Murdock 1987). A number of studies have shown that there are serial position effects in the memory scanning task (Corballis 1967; Morin et al. 1967; Murdock 1968; Forrin and Morin 1969; Clifton and Birenbaum 1970; Burrows and Okada 1971; Kirsner and Craik 1971; Klatzky et al. 1971; Corballis et al. 1972; Baddeley and Ecob 1973; Forrin and Cunningham 1973; Wingfield 1973; Aubé and Murdock 1974; Koh et al. 1977). When recognition accuracy is plotted as a function of the serial position of an item in the list, items in the first and/or the last positions are shown to be better remembered (Corballis 1967; Morin et al. 1967; Murdock 1968). A similar pattern has been observed for free and serial recall (Roberts 1986; Lewandowsky and Murdock 1989). This superior memory for the first items has been termed the primacy effect, and for the last items, the recency effect. Reaction time in the scanning task can have a similar U-shaped function; RTs to the items presented in the first and/or the last positions in the list are faster than to the items presented in the middle positions (Corballis 1967; Morin et al. 1967; Forrin and Morin 1969; Clifton and Birenbaum 1970; Burrows and Okada 1971; Klatzky et al. 1971; Corballis et al. 1972; Baddeley and Ecob 1973; Forrin and Cunningham 1973; Wingfield 1973; Aubé and Murdock 1974; Koh et al. 1977). In short-term memory tasks involving memory scanning, both primacy and recency effects have been reported, but recency effects are more often observed (Corballis 1967; Morin et al. 1967; Murdock 1968; Forrin and Morin 1969; Clifton and Birenbaum 1970; Baddeley and Ecob 1973; Forrin and Cunningham 1973; Lewandowsky and Murdock 1989).

The modality of presentation of the to-be-remembered items has a significant effect on the serial position function. Recognition or recall for items presented in the last portion of a list is better for auditory than for visual presentations, indicating that the recency effect is modality dependent (Murdock 1968; Craik 1969; Murdock and Walker 1969; Kirsner and Craik 1971; Burrows 1972; Watkins and Watkins 1977; Drewnowski and Murdock 1980; Crowder 1986; Roberts 1986). This finding has been given as support for the hypothesis that short-term memory is primarily acoustic or phonological in nature (Conrad 1964; Wickelgren 1965; Laughery and Fell 1969; Sperling and Spielman 1970; Spoehr and Corin 1978; Shand and Klima 1981; Salamé and Baddeley 1982; Greene 1986; Roberts 1986). According to this theory, the phonological components of words can be directly encoded into short-term memory when presented in the auditory mode, but this same material, when presented visually, necessitates translation or recoding into an auditory or phonological store, and thus requires extra processing and reduces the capacity of the short-term store. Different memory mechanisms also may be required for processing non-verbal than for verbal auditory (Shallice and Warrington 1974; Roberts 1986) and visual (Potter and Levy 1969; Shafer and Shiffrin 1972; Loftus 1974) material.

The purpose of our study was to examine serial position effects in a memory scanning task as a function of both the modality of presentation (visual and auditory) and the type of item (verbal and non-verbal), using both behavioral (RT and accuracy) and ERP measures. The finding of serial position and/or modality effects in the late positive component of the ERP to the probes would suggest that these effects are occurring early, at a level of information processing prior to

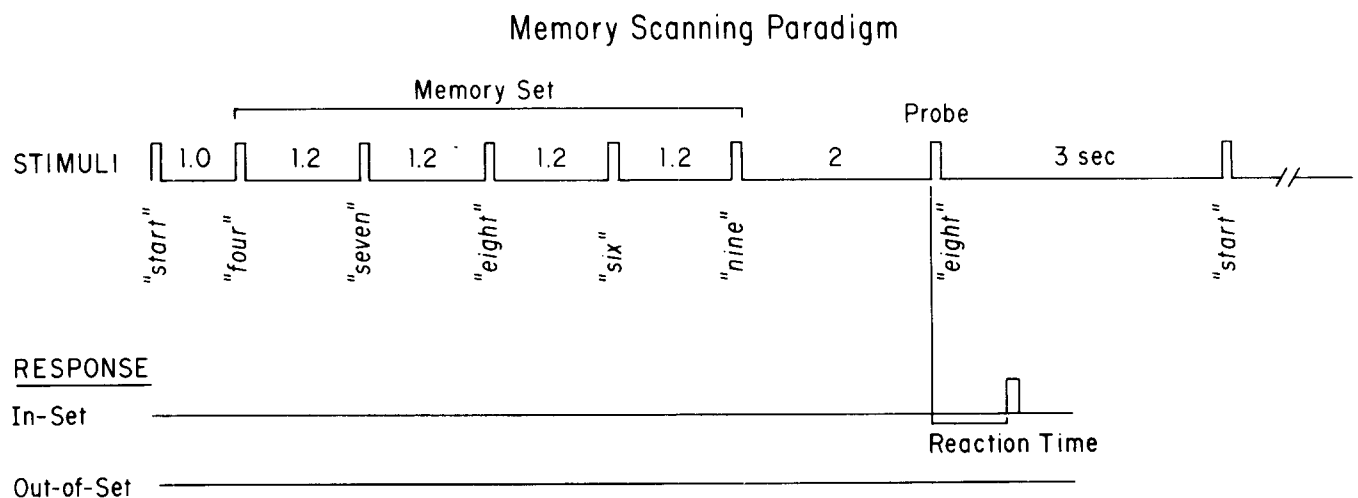


Fig. 1. Sample stimulus sequence showing timing of stimulus presentation. After the word 'start,' which signaled the beginning of a trial, the 5 digits contained in the memory set were presented, followed by the probe digit. Subjects indicated whether the probe was in-set or out-of-set by pressing the appropriate reaction time button. In this example, the correct response was in-set. Event-related potentials were averaged to the probes according to their position in the memory set, and to the memory set items in positions 1, 3 and 5.

response selection. This information would provide additional evidence regarding the validity of the serial exhaustive memory scanning model and the role of stimulus modality and type in short-term memory. Serial position effects were examined not only for the probes, but also for the memory set items. It has been suggested that the serial position effects seen in the memory scanning task may arise during the encoding of the memory items, rather than in the comparison stage (Sternberg 1975). In addition to comparison and retrieval processes, the ERP can provide information regarding encoding processes during memorization, and thus may help to resolve the locus of the serial position effects. The results will bear on whether differential processing of the memory set items occurs as a function of their position in the list.

## Methods

### *Subjects*

Nine normal young adults ranging in age from 18 to 39 years (mean age = 26.2, S.D. = 5.9) participated in the study. The subjects were students or employees at the University of California, Irvine, CA. Participants reported no neurological or hearing problems and all had normal to corrected-to-normal vision. The Mini-Mental State exam (Folstein et al. 1975) was given to all subjects and none scored below 29 out of a possible 30 (mean = 29.8, S.D. = 0.4). Eight of the subjects were right handed.

### *Procedure*

A memory scanning task modified from Sternberg (1966, 1969, 1975) was used (see Fig. 1). Details of the procedure are provided in Starr and Barrett (1987) and Pratt et al. (1989a, b, c), and a brief description will be provided here. Subjects were presented with 5 items (the memory set) followed by the probe stimulus. They indicated whether or not the probe was a member of the previously presented memory set by pressing 1 of 2 buttons to in-set (positive) probes and the other button to out-of-set (negative) probes as quickly and accurately as possible. Three types of stimuli generated by a micro-processor were used: verbal digits presented both auditorily and visually, and musical notes presented auditorily. The items were drawn from a repertoire of 9 stimuli including, for verbal auditory and visual presentations, digits 1 through 9, and, for non-verbal presentations, notes Middle C through D, 1 octave above. The probability that the probe was contained in the memory set was 0.50 and positive probes occurred with equal probability for each position in the memory set. Visual stimuli subtending a visual angle of 20" × 40" were presented on a video monitor. Auditory stimuli were presented through earphones at an intensity of ap-

proximately 60 dB nHL. For each stimulus type, memory sets and probes were presented in 4 blocks of 20 trials with a fixed set size. Stimulus durations were 100 msec for the notes and 500 msec for auditory and visual digits.

Scalp electrical potentials were recorded from mid-line electrode sites Fz, Cz, and Pz referenced to linked earlobes at a bandpass of 0.1–100 Hz (3 dB down, 6 dB octave slopes). Eye movements were monitored from electrodes above and below the right eye. The 4 channels of EEG data were digitized over a sweep time of 1.28 sec (dwell time = 5.0 msec) for the probes, and 0.96 sec (dwell time = 3.75 msec) for the memory set items, beginning 120 msec (baseline period) before stimulus onset. Single trials were stored on disk for subsequent data analysis. Subjects were tested in a sound attenuating chamber in a seating position with their eyes open.

For each stimulus type, ERPs, RTs, and the percentage of correct responses to correctly identified in-set probes were separately averaged according to their position (1–5) in the memory set, yielding 5 separate averages for each stimulus type for each measure. Since 80 trials were presented, 40 of which were in-set and 40 out-of-set, a maximum of 8 trials could be averaged as a function of the serial position of the in-set probe in the memory set. The amplitude of the potentials to the probes were large (see Fig. 2), allowing clear averages with such a small number of trials. ERPs to the memory set items in positions 1, 3 and 5 also were separately averaged. The averages for the memory set items as a function of position comprised up to 80 trials.

Measures of baseline-to-peak amplitudes and latencies were performed on the filtered (zero phase shift, low-pass digital filter with a cutoff at 17 Hz) averaged wave form for both the probes and the memory set items. Latencies were measured from stimulus onset, and amplitudes were measured relative to the mean voltage during the prestimulus baseline period. The late positive peak was defined as the maximum positivity following the initial N1-P2-N2 sequence. The maximum positivity criterion was applied to recordings from each of the leads, and resulted in the separation of the peak into an earlier frontal positivity and a later parietal positivity. For the memory set items, the late potential was negative to auditory digits and notes at the frontal recording site.

Since the late potential to the probes and the memory set items was a sustained shift lasting up to several hundred milliseconds, an additional measure of average amplitude (relative to baseline) over a 500 msec window was determined for the late component of the ERPs to both the probes and the memory set items. Window size and starting points for the mean amplitude measure were determined from the grand averages across subjects, and included the sustained positivity (or negativity) of the potential. For the sustained positivity at Pz to

the probes, the starting point for the window was 450 msec for auditory digits, 400 msec for visual digits, and 420 msec for notes. For the memory set items, the window starting point was 300 msec.

#### Data analysis

The effects of serial position on RTs, response accuracy, and the late component of the ERP were evaluated for each stimulus type and for both the frontal and parietal electrode locations using analysis of variance (ANOVA) procedures with repeated measures (position; stimulus type  $\times$  position; electrode  $\times$  stimulus type  $\times$  position). Post hoc comparisons of the means were carried out using the Newman-Keuls procedure (Winer 1971). Significance levels were set at  $P < 0.05$ .

## Results

#### RT and response accuracy

Mean RTs to correctly identified in-set probes and response accuracy (percent correct) are plotted in Fig. 2C as a function of the position of the probes in the memory set. Table I gives a summary of the significant results for performance. Significant serial position effects on RTs were found for auditory digits ( $P = 0.012$ ) and notes ( $P < 0.001$ ). For auditory digits, RTs to probes were shortest when the probe item was presented last in the memory set, and longest for probes presented in the second position, showing a significant recency effect. Mean RTs (and S.D.s) for auditory digits were 737 (123), 840 (189), 779 (137), 743 (132), and 674 (154)

TABLE I

Summary of significant serial position effects for performance measures (reaction time, accuracy), and ERPs to probes<sup>a</sup> and memory set items for auditory digits, visual digits, and notes.

	Auditory digits	Visual digits	Notes
<b>Performance</b>			
Reaction time	5 < 2	N.S.	5 < 1, 2, 3, 4
Accuracy	N.S.	N.S.	1, 2, 3 < 4, 5
<b>Probes<sup>b</sup></b>			
Pz peak amplitude	5 > 2, 3, 4	N.S.	N.S.
Pz average amplitude	5 > 2, 4	N.S.	N.S.
<b>Memory set items<sup>c</sup></b>			
Fz peak amplitude	5, 3 < 1	5, 3 < 1	5, 3 < 1
Fz average amplitude	5, 3 < 1	5, 3 < 1	5, 3 < 1

<sup>a</sup> The table is arranged so that the numbers refer to the position of the probe in the memory set. For example, the entry under auditory digits and performance (reaction time), 5 < 2, indicates that reaction time to the probe when it was in the fifth position in the memory set was significantly faster than when it was in the second position.

<sup>b</sup> Serial position effects were not significant for Fz peak or average amplitude, or for Fz or Pz latency.

<sup>c</sup> Serial position effects were not significant for Pz peak or average amplitude, or for Fz or Pz latency.

msec for positions 1–5, respectively. For notes, RTs to probes decreased from position 1 to position 5, and RTs at position 5 were significantly shorter than RTs at all the other positions, also showing a recency effect. Mean RTs (and S.D.s) for notes were 1073 (303), 1025 (252), 973 (147), 905 (130), and 677 (115) msec for positions 1–5, respectively. For visual digits, the effects of serial position on RTs were not significant ( $P = 0.064$ ). Response accuracy yielded a significant recency effect for notes ( $P = 0.0001$ ), with accuracy at positions 4 and 5 better than at positions 1, 2 and 3. Response accuracy means (and S.D.s) for notes were 67 (25), 68 (17), 80 (12), 94 (6), and 100 (0) % at positions 1–5, respectively. Response accuracy was not significantly affected by serial position for auditory or visual ( $P = 0.06$ ) digits.

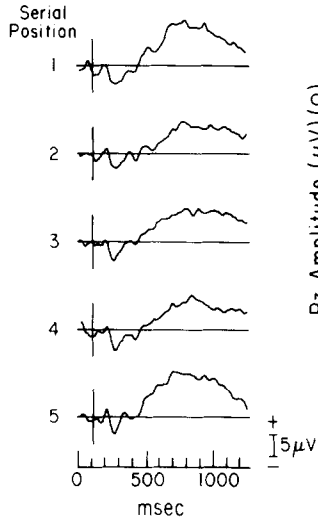
#### ERPs to probes

The potentials to the probes yielded a late sustained positivity, consisting of an early frontally distributed component and a larger and later parietal component.

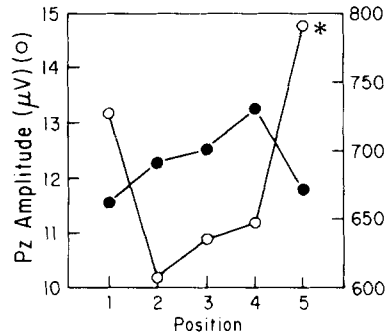
Parietal ERPs to correctly identified in-set probes grand averaged over subjects are shown in Fig. 2A for auditory digits, visual digits, and notes as a function of the serial position of the probe in the memory set. Baseline-to-peak amplitudes of the late parietal positivity and latency from stimulus onset as a function of serial position are also plotted (Fig. 2B). A summary of the significant ERP results for the probes is given in Table I. Significant effects of serial position on the parietal positivity baseline-to-peak amplitudes were observed for auditory digits ( $P = 0.015$ ). Late positivity amplitudes to probes presented in the last position in the memory set were significantly larger than to probes presented in positions 2, 3 and 4, showing a significant recency effect. Mean parietal positivity amplitudes (and S.D.s) for auditory digits were 13.2 (4.7), 10.2 (4.0), 10.9 (6.2), 11.2 (5.4), and 14.8 (6.5)  $\mu\text{V}$  for positions 1–5, respectively. While a primacy effect was suggested by the finding that peak amplitudes to probes in the first position did not differ significantly from amplitudes to probes in the last position, amplitudes to probes in the first position also did not differ from amplitudes to probes in positions 2, 3 and 4. Thus it could not be concluded that there was a significant primacy effect. For auditory digits, the peak latency from stimulus onset of the parietal component to the probes also varied with their serial position in the memory set (Fig. 2B, auditory digits), but the differences did not reach significant levels. Mean parietal component latencies (and S.D.s) were 663 (100), 692 (82), 702 (115), 731 (81), and 672 (130) msec for positions 1–5, respectively. For both visual digits and notes, the peak amplitude of the parietal positivity to the probes did not change significantly with serial position; latency from stimulus onset was also not significantly affected by serial position for visual digits and notes. The baseline-to-peak amplitude

## Auditory Digits - Probes

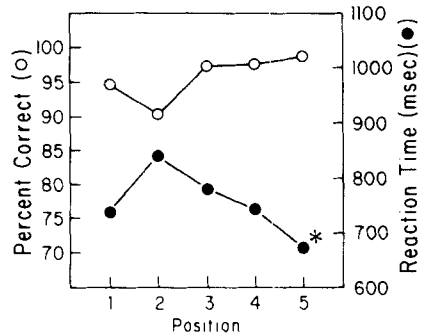
A. Event-Related Potential



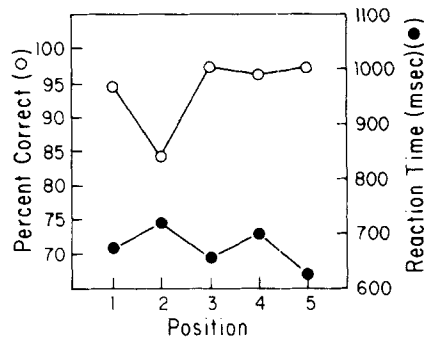
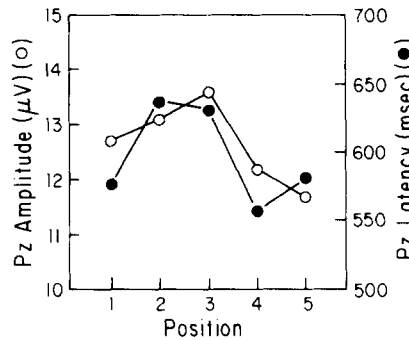
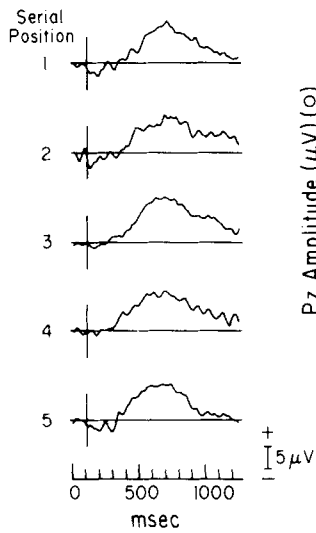
B. Late Component (Pz)



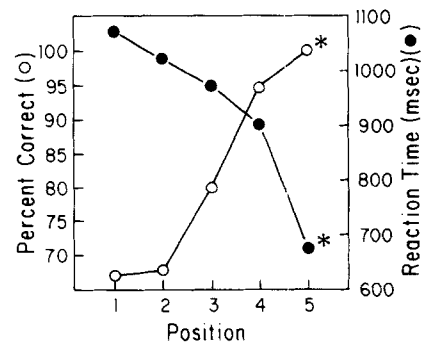
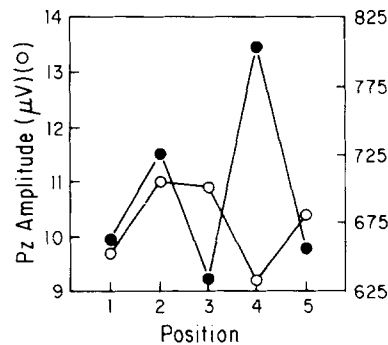
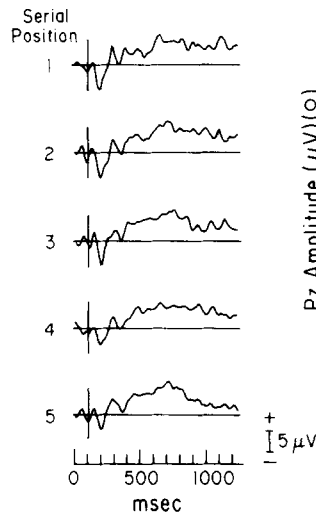
C. Performance



## Visual Digits - Probes



## Notes - Probes



and latency from stimulus onset of the frontal positivity to the probes did not change significantly as a function of serial position for any of the 3 stimulus types.

The analysis of the average amplitude of the late positivity to the probes at Pz over a 500 msec window showed serial position effects similar to those found in the baseline-to-peak amplitude measures at Pz. For auditory digits, the measure of average amplitude showed a significant recency effect ( $P = 0.03$ ) (Fig. 3). Mean average amplitudes (and S.D.s) were 8.4 (5.0), 5.6 (4.2), 6.7 (5.1), 5.6 (6.0), and 9.4 (4.7)  $\mu\text{V}$  for positions 1–5, respectively. Average amplitude to probes presented in the last position in the memory set was larger than to probes presented in the second and fourth positions. As for the baseline-to-peak measure, average amplitude in position 1 was not different than average amplitude in position 5, or from average amplitude in positions 2, 3 and 4. The effects of serial position on average amplitude were not significant for visual digits or for notes<sup>2</sup>.

#### ERPs to memory set items

The potentials to the memory set items yielded a small sustained potential which was positive in the parietal region for visual digits and notes, but was greatly attenuated or absent for auditory digits. The frontal sustained potential to the memory set items was positive only to the visual digits, and more often negative than positive in the auditory modality.

<sup>2</sup> For both the baseline-to-peak and average amplitude of the late parietal potential to the visual digits and notes, the estimated power of the  $F$  test at a significance level of 0.05, or the probability of rejecting the null hypothesis of 'no effect' due to serial position, was less than 0.3 (Kirk 1968; Keppel 1973; Cohen 1988). For our sample size and a significance level of 0.05, a specified power of 0.8, for example, would detect an estimated 'effect size' (defined as the standard deviation of the standardized population means) of approximately one-half of the within population standard deviation of the observations (Cohen 1988). Assuming 'intermediate variability' (or means equally spaced over the range of means) (Cohen 1988), this corresponds to an estimated range of population means between 3.8 and 4.7  $\mu\text{V}$  for our data, using the square root of the mean square error term in the  $F$  ratio as an estimate of the within population standard deviation (Kirk 1968; Cohen 1988). 'Acceptance' of a null hypothesis requires a high level of power, but quite large sample sizes are needed to establish a negligible or very small effect (e.g., Cohen 1988); it is more appropriate to say that the null hypothesis cannot be rejected at the level of significance used. In contrast, for the baseline-to-peak and average amplitudes of the late parietal potential evoked by the auditory digits the estimated power of the  $F$  test was approximately 0.7.

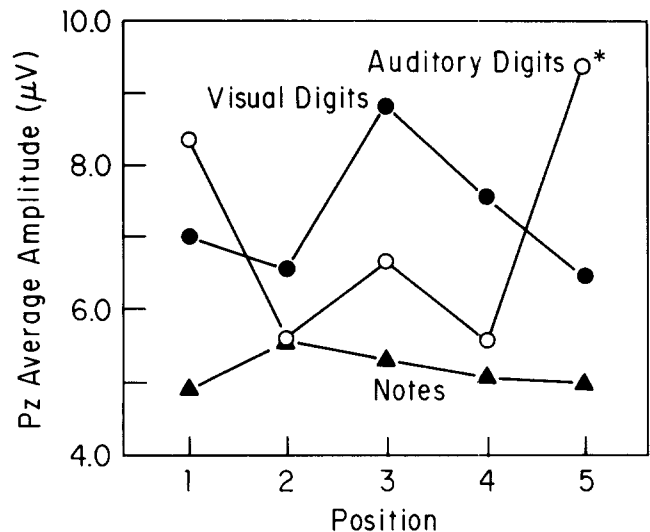


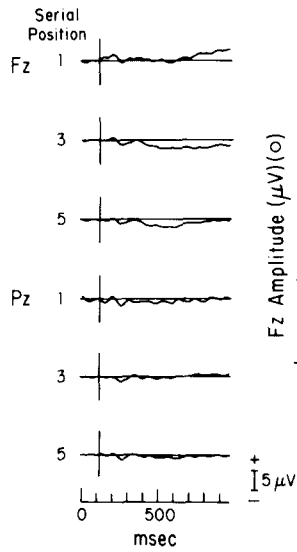
Fig. 3. Average amplitude of the late parietal potential to in-set probes as a function of the serial position of the probe in the previously presented memory set for auditory digits, visual digits, and notes. Average amplitude was determined over a 500 msec window. Window size and starting point were determined from the grand averages. An asterisk indicates a significant serial position effect ( $P < 0.05$ ).

Serial position effects were evident when these potentials were selectively analyzed. Fig. 4A contains the grand averaged ERPs to the memory set items in positions 1, 3 and 5 for Fz and Pz to auditory digits, visual digits and notes (panel A, left column). In panels B and C, baseline-to-peak amplitude and latency from stimulus onset of the late potential at Fz and Pz, respectively, are plotted as a function of the serial position of the memory set item for each of the 3 stimulus types. Table I provides a summary of the significant ERP results for the memory set items. Significant effects of serial position were found only for Fz amplitudes. For each stimulus type, the peak amplitudes of the late potential to memory set items presented in the first position were less negative (in the case of the visual digits, more positive) than amplitudes to memory set items presented in the third and last positions ( $P < 0.01$ ). The mean amplitudes (and S.D.s) were 0.77 (2.45),  $-0.80$  (1.63), and  $-0.72$  (1.44)  $\mu\text{V}$  for auditory digits; 3.22 (2.69), 1.53 (1.72), and 1.59 (1.02)  $\mu\text{V}$  for visual digits; and  $-0.22$  (2.15),  $-2.17$  (1.65), and  $-0.96$  (1.93)  $\mu\text{V}$  for notes, for positions 1, 3 and 5, respectively. The effects of serial position of the memory set item on Pz peak amplitudes were not significant. Latency was not significantly affected by serial position at either Fz or Pz.

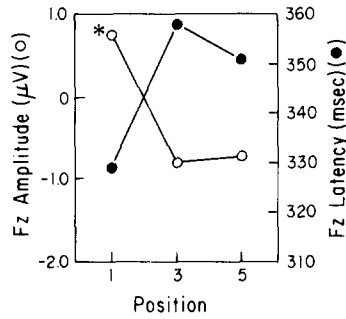
Fig. 2. In A, grand-averaged event-related potentials to in-set probes are shown for Pz as a function of the serial position of the probe in the previously presented 5-item memory set. In B, baseline-to-peak amplitude and latency from stimulus onset of the late parietal potential are shown as a function of serial position. C shows reaction time and response accuracy (percent correct) according to serial position. The 3 panels are shown for auditory digits, visual digits, and notes, respectively. An asterisk indicates a significant serial position effect ( $P < 0.05$ ).

## Auditory Digits-Memory Set Items

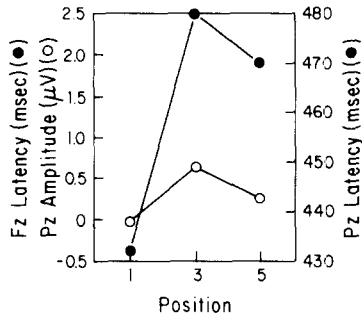
### A. Event-Related Potential



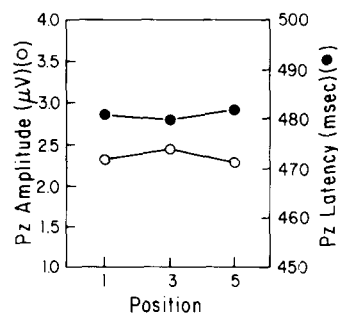
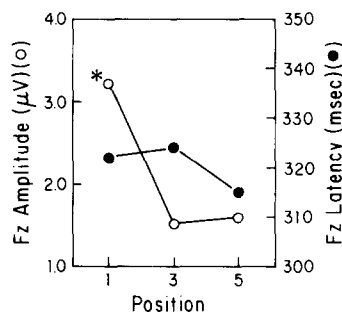
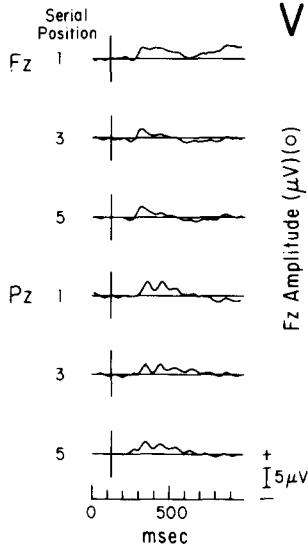
### B. Late Component (Fz)



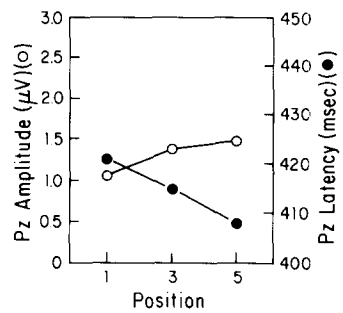
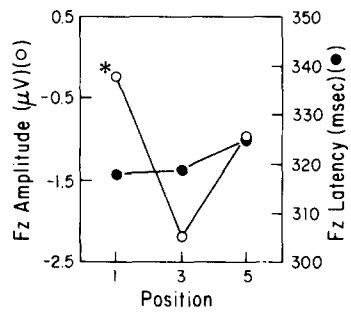
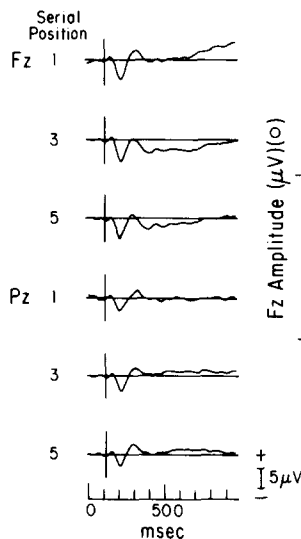
### C. Late Component (Pz)



## Visual Digits-Memory Set Items



## Notes-Memory Set Items





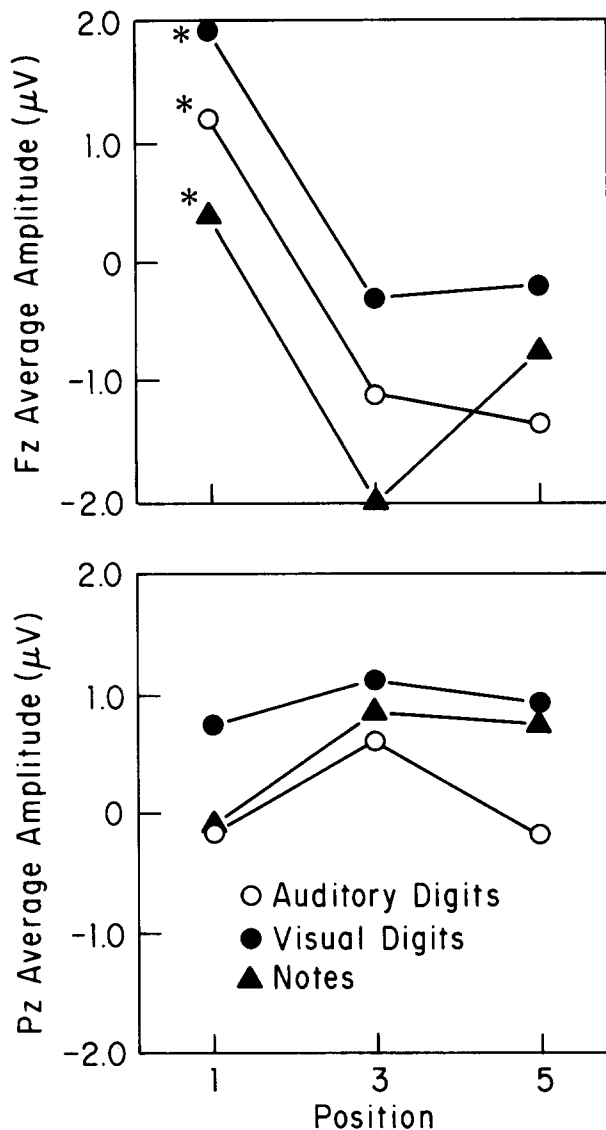


Fig. 5. Average amplitude of the frontal and parietal late components to the memory set items in positions 1, 3 and 5 for auditory digits, visual digits, and notes. Average amplitude was determined over a 500 msec window. Window size and starting point were determined from the grand averages. An asterisk indicates a significant serial position effect ( $P < 0.05$ ).

Fig. 5 shows the average amplitude over a 500 msec window of the frontal and parietal late potential to the memory set items in positions 1, 3 and 5 for each of the 3 stimulus types. As for the peak amplitude measure, significant effects of serial position on average amplitude of the late potential to the memory set items were

observed only for Fz. For each stimulus type, the average amplitude of the frontal component was significantly less negative to memory set items presented in the first position compared to memory set items presented in the third and last positions ( $P < 0.001$ ). The mean average amplitudes (and S.D.s) were 1.18 (3.57), -1.09 (1.11), and -1.33 (0.66)  $\mu\text{V}$  for auditory digits; 1.91 (3.86), -0.28 (1.86), and -0.18 (1.34)  $\mu\text{V}$  for visual digits; and 0.41 (2.54), -2.01 (1.06), and -0.75 (1.46)  $\mu\text{V}$  for notes, for positions 1, 3 and 5, respectively.

While measures of baseline-to-peak and average amplitude yielded similar results for both the probes and the memory set items, the measure of average amplitude probably better characterized the sustained nature of the late component, especially for the memory set items.

### Discussion

#### Probe items

The findings of this study showed that serial position effects were reflected in measures of both ERPs and RTs to the probe items during memory scanning. Significant recency effects were observed for RT and for the amplitudes of a late parietal positivity to digits presented in the auditory but not in the visual modality. For the musical notes, RTs to the probes and measures of response accuracy also showed significant recency effects, but ERPs to the probes did not vary significantly with serial position. The findings of our study suggest that serial position effects observed in the behavioral response can also be detected earlier, at the level of stimulus evaluation as reflected in a late positive parietal component of the ERP.

The late positivity in our study appears similar in latency range and scalp distribution to the definition given to a parietal positivity termed the P300 component (Donchin et al. 1978; Sutton and Ruchkin 1984), and observed in an infrequent stimulus classification or oddball paradigm (e.g., Ritter et al. 1968; Ritter and Vaughan 1969; Picton and Hillyard 1974; Squires et al. 1975), and in various types of memory tasks (Warren 1980; Chapman et al. 1981; Warren and Wideman 1983; Karis et al. 1984; Johnson et al. 1985; Neville et al. 1986; Friedman and Sutton 1987). In a recognition task, the amplitude of P300 to 'old' words is larger (Sandquist et al. 1980; Karis et al. 1984; Smith et al. 1986; Rugg and Nagy 1989) and its latency is shorter (Warren 1980; Johnson et al. 1985) than to 'new' words.

Fig. 4. In A, grand-averaged event-related potentials to the memory set items in positions 1, 3 and 5 are shown for Fz and Pz. In B, baseline-to-peak amplitude and latency from stimulus onset of the late frontal component are shown as a function of serial position. C shows baseline-to-peak amplitude and latency from stimulus onset of the late parietal component as a function of serial position. The 3 panels are shown for auditory digits, visual digits, and notes, respectively. An asterisk indicates a significant serial position effect ( $P < 0.05$ ).

Moreover, those words that are subsequently recognized elicit larger P300 amplitudes on initial presentation than words not subsequently recognized (Karis et al. 1984; Johnson et al. 1985; Fabiani et al. 1986; Neville et al. 1986; Paller et al. 1987). Data from Johnson et al. (1985) suggest that as recognition performance improves, P300 amplitude increases, accompanied by decreases in P300 latency and RT. Taken together, these results imply that larger P300 responses are associated with 'stronger' memory traces, accompanied by rapid stimulus classification times and increased accuracy (Johnson et al. 1985). The results of our study are in agreement with these findings, but only for the auditory modality and only for verbal material; larger late parietal components of the ERP and faster RTs were associated with probe items presented in the recency portion of the list to be memorized, suggesting that stronger memory traces were associated with the more recently presented items. This interpretation is consistent with a trace strength model of memory processing, which has received some support in accounting for serial position effects in performance in the memory scanning task (Wickelgren and Norman 1966; Corballis et al. 1972; Corballis 1979; Hockley and Murdock 1987).

The amplitude of P300 also has been associated with the amount of attention allocated to a task (Israel et al. 1980; Wickens et al. 1983; Hoffman et al. 1985), perhaps reflecting automatic vs. controlled attentional strategies (e.g., Schneider and Shiffrin 1977; Shiffrin and Schneider 1977; Hoffman et al. 1985; Kramer et al. 1986). Automatic and controlled processes are differentiated according to the degree of attentional capacity or effort each requires (e.g., Schneider and Shiffrin 1977; Hasher and Zacks 1979). Using this schema of the late parietal positivity and/or the P300, our findings suggest that the more recently presented items receive more attention or processing capacity, and possibly 'deeper' processing during memory scanning (Burrows and Okada 1971; Craik and Lockhart 1972; Baddeley and Ecob 1973; Glenberg and Adams 1978; Whitten 1978), and are, in turn, associated with larger late parietal components to the probes.

Our findings showed evidence of modality-specific serial position effects in the ERP to the probes that also reflected the type of item being memorized. Measures of the amplitude of the parietal positivity to the probes showed significant recency effects only for digits presented auditorily, but not for visual digits or auditorily presented notes. Similarly, in behavioral studies using accuracy and RT measures, recency effects are more pronounced when items are presented in the auditory compared to the visual modality (Murdock 1968; Craik 1969; Murdock and Walker 1969; Kirsner and Craik 1971; Burrows 1972; Watkins and Watkins 1977; Drewnoswski and Murdock 1980; Crowder 1986; Ro-

berts 1986). Such modality effects have led to a theory that the contents of short-term memory are coded auditorily or phonologically, resulting in a larger capacity for auditory information (Conrad 1964; Wickelgren 1965; Laughery and Fell 1969; Sperling and Spielman 1970; Spoehr and Corin 1978; Shand and Klima 1981; Salamé and Baddeley 1982; Greene 1986; Roberts 1986), whereas visual material must be translated into an auditory or phonological code for storage in short-term memory. Findings of larger overall parietal positivity amplitudes to the probes for visual digits than for auditory digits or notes (Pratt et al. 1989a, b) support the idea that more processing is needed for these items during retrieval, if theories regarding the association between the amplitude of the late positive component and the allocation of attention are accepted (Israel et al. 1980; Wickens et al. 1983; Hoffman et al. 1985; Kramer et al. 1986; Donchin 1987). Furthermore, when 'type I' or rote maintenance rehearsal of the items in short-term memory is used, it appears to strengthen the phonemic as opposed to the semantic aspects of the memory trace (Craik and Lockhart 1972; Glenberg and Adams 1978). Other related theories have proposed that a brief precat-egorical auditory sensory store complements the short-term store (Crowder and Morton 1969; Greene and Crowder 1984), or that there are separate auditory and visual short-term stores, with the capacity of the auditory store being larger than the visual store (Murdock and Walker 1969; Penney 1975). More recently, evidence of long-term recency and modality effects in recall has supported theories based on the temporal distinctiveness of the items (Glenberg and Swanson 1986), or on contextual retrieval cues (Glenberg 1984). In any case, our findings provide electrophysiological evidence of modality-specific processes in short-term memory.

A dissociation between RT and the late parietal component responses to the probes was observed for the musical notes; both RT and response accuracy showed recency effects, whereas the late parietal positivity did not. This suggests that the recency effect for the notes reflected response selection rather than comparison or retrieval processes. Additionally, as measures of accuracy indicated, the note task was more difficult than the digit tasks, especially for items occurring early in the memory set. More difficult or complex tasks can increase the amplitude of the late positivity (Wickens et al. 1983; Johnson 1986), perhaps reflecting an increase in processing requirements. A greater effect of these factors on the late positivity to the items occurring early in the list than to the last items could reduce the recency effects seen in the ERP. The absence of a recency effect in the ERP to the notes also may suggest that, like visual material, auditorily presented notes require recoding into short-term memory, or are processed differently. In support of the hypothesis that

notes require additional processing, there is behavioral evidence that the recency advantage for auditorily compared to visually presented information may not always be as clear for non-verbal as for verbal input (Roberts 1986). Moreover, patients with a deficit of auditory verbal short-term memory show impaired retention for letters but not for meaningful sounds, suggesting that the auditory short-term system is primarily verbal in content (Shallice and Warrington 1974).

Evidence that positive and negative probes produce parallel RT (Sternberg 1966, 1969, 1975; Burrows and Okada 1971; Klatzky et al. 1971; Burrows 1972; Wingfield 1973; Adam and Collins 1978; Ford et al. 1979) and late positive component latency (Marsh 1975; Gomer et al. 1976; Adam and Collins 1978; Ford et al. 1979; Pratt et al. 1989a, b) slopes as a function of set size has been cited as support for the serial exhaustive memory scanning model proposed by Sternberg (1966, 1969, 1975). In contrast, reports that the slopes are not parallel (Forrin and Morin 1969; Corballis et al. 1972; Aubé and Murdock 1974; Elkind and Corballis 1986) favor a concept that the search is self-terminating (Kirsner and Craik 1971; Hacker 1980). Serial position effects in the memory scanning task are also inconsistent with the serial exhaustive model, which predicts flat serial position functions (Sternberg 1969). In addition to the proposal that the search is self-terminating, other alternatives to a serial exhaustive hypothesis include trace strength models, in which familiarity or the strength of the memory trace influences the speed and accuracy of retrieval, and parallel processing models, in which probe and memory set items are compared in parallel rather than serially (Wickelgren and Norman 1966; Burrows and Okada 1971; Corballis et al. 1972; Baddeley and Ecob 1973; Atkinson and Juola 1974; Cavanagh 1976; Ratcliff 1978; Corballis 1979; Gillund and Shiffrin 1984; Hockley and Murdock 1987). Still other theories stress variations in the amount of attention or processing capacity allocated to the various items in a list, or in processing strategies involving 'depth of processing' (Atkinson et al. 1969; Burrows and Okada 1971; Craik and Lockhart 1972; Baddeley and Ecob 1973; Glenberg and Adams 1978). Our ERP data for the probes do not necessarily favor a particular alternative model, but, by confirming the recency effect for auditory digits in both RT and ERP measures, provide additional evidence contradicting the theory that the list is scanned serially and exhaustively. Since our data showed no significant differences for either RT or ERP measures between positive and negative probes, however, which would be predicted by the serial exhaustive model, a definitive statement regarding the model is not possible. Moreover, the absence of significant recency effects in the ERP for both visual digits and notes indicates that different memory processes may be employed for these items than for verbal auditory material.

### *Memory set items*

Our findings showed significant serial position effects in the ERPs to the memory set items. In contrast to the modality-specific effects in the ERPs to the probes, each stimulus type showed a position effect at the frontal recording site. The amplitude of the late sustained component became more negative (in the case of the baseline-to-peak measure for the visual digits, less positive) to the memory items in the third and fifth serial positions compared to the first. Thus there were position effects occurring prior to memory scanning, at the level of encoding or memorization.

The frontal negativity accompanying the memory set items has several features analogous to an endogenous attention-related negativity termed the processing negativity (PN), or Nd (Näätänen et al. 1978; Näätänen and Mitchie 1979; Hansen and Hillyard 1980; Näätänen 1982; Ritter et al. 1984; Alho et al. 1987; Näätänen and Picton 1987; Picton and Hillyard 1988). In selective attention tasks, the amplitude of the PN reflects the distribution of attention or the allocation of processing capacity among 2 or more 'channels' of information (Hillyard et al. 1973; Okita 1979; Picton and Hillyard 1988). Two components of the PN have been identified, including an early, short-duration, centrally distributed component, which is prominent when stimuli are similar, and a later (approximately 250–350 msec), sustained (up to several hundred milliseconds), frontally distributed component, which becomes apparent as the stimuli become distinctly identifiable as targets (Näätänen and Mitchie 1979; Hansen and Hillyard 1980; Näätänen 1982). The second of these 2 components is similar in latency range and scalp distribution to the frontal negativity to the memory set items observed in the present experiments. It has been suggested that the early PN reflects target-feature identification and stimulus selection, while the later frontal PN reflects further processing or selective maintenance and rehearsal of the stimuli identified as targets (Näätänen 1982; Hillyard and Kutas 1983; Picton and Hillyard 1988). In our study, but only for auditory digits, an increased frontal negativity seen to the most recent memory set items was associated with a larger parietal positivity to the probe. Using the interpretation given for the frontal PN, perhaps more attentional capacity was allocated to processing the recent items in the memory scanning task during encoding and memorization, or more attention was directed toward the selective rehearsal of these items, leading to faster and more accurate comparisons during the retrieval stage, which in turn were associated with larger late parietal positivities (e.g., Hansen and Hillyard 1980).

Contrary to this interpretation, however, additional processing or rehearsal during memorization as reflected in the attention-related negativity was not consistently associated with better performance during re-

trieval in our memory scanning task. First, a negativity was seen to the third as well as to the fifth memory set item, and, for auditory digits, larger parietal positivities and better performance were not associated with the third item. Second, the association between more frontal negativity to the memory set items and increasing parietal positivity to the probes was present only for auditory digits. Third, for the baseline-to-peak measure for visual digits, the frontal late component did not become more negative, but rather less positive. Whether this trend for visual digits was a result of an underlying negativity, or a different process, such as a reduction of the amplitude of the late positive component with increasing memory load requirements (e.g., Brookhuis et al. 1981; Donchin 1987), is not clear. Attention-related negativities similar to the PN seen in the auditory modality and related to the degree of processing required have been observed in the visual modality (Kramer et al. 1986; Horst et al. 1987; Looren de Jong et al. 1987; Picton and Hillyard 1988), and these negativities may account for the diminished positivities seen with high memory load (Okita et al. 1985; Looren de Jong et al. 1987). In an alternative interpretation, if the late frontal component associated with the first items in the memory set is interpreted as more positive, rather than less negative, the serial position effects seen in the ERP to the memory set items could be interpreted as supporting a primacy effect. Our data do not allow a definitive conclusion regarding the source of the serial position effects in the memory set items. However, especially for the auditory modality, the morphology, distribution, and latency of our frontal component to the memory set items support its interpretation as an attention-related negativity which increases in amplitude with the amount of processing required, or the degree of memory load. In any case, our finding of modality-specific serial position effects to the probes but not to the memory set items is consistent with the view that the modality effects are occurring postcategorically, and reflect retrieval processes (Baddeley and Hitch 1977; Watkins and Watkins 1977; Glenberg and Swanson 1986; Greene 1986).

A second fronto-central negativity associated with information processing, termed the mismatch negativity (MMN) (Sams et al. 1984; Näätänen and Picton 1987), also might be related to the frontal negativity observed in our study to the memory set items. The MMN can appear in tasks with no attentional demands (Näätänen 1982), and when the subject must attend to the stimulus, a third negativity, N2b, can follow the MMN (Sams et al. 1984; Näätänen and Picton 1987). It is possible that an MMN, perhaps followed by N2b, was generated to the memory set items in our study, which increased in amplitude toward the end of the list as more mismatches among the items had occurred (e.g., Kramer et al. 1986). Thus a number of negativities, including the

PN, MNN, and N2b, may have contributed to the negative components seen in our memory scanning task, and these negativities may reflect a combination of automatic and controlled processing demands (e.g., Ford and Hillyard 1981; Kramer et al. 1986; Näätänen and Picton 1987).

Our findings suggest that the effects of serial position are seen during both the encoding and retrieval stages of the memory scanning task. At least for verbal material presented auditorily, the results present evidence contrary to a serial exhaustive model. If changes in the amplitude of the parietal positivity to the probes and the frontal negativity to the memory set items are indeed indicative of the strength of the memory trace and/or the amount of processing required by a task, a theory which emphasizes trace strength or level of attentional capacity might be more consistent with our data. Also, the finding of modality effects in the late positive parietal component to the probes, as well as in behavioral measures, is consistent with the theory that the short-term store is coded phonologically, with a reduced capacity for visual, and perhaps also for non-verbal auditory material. Further studies are needed to resolve these issues. The finding in the present study that measures of a late component of the ERP are systematically related to a phenomenon of memory such as the serial position effect provides further evidence supporting the association of this positivity with cognitive processes involving memory.

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