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## Brain potentials in a memory-scanning task. I. Modality and task effects on potentials to the probes <sup>1</sup>

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**Summary** Event-related potentials were measured in normal young subjects during a memory-scanning paradigm modified from one proposed by Sternberg. The stimuli used were verbal (digits) and non-verbal (musical notes) with the verbal stimuli and notes presented acoustically and the verbal stimuli also presented visually. In this paradigm each set of stimuli was presented for memorization, and then, after a 2 sec interval, a probe item appeared and was identified by the subject as belonging or not belonging to the memorized set. Memorized set sizes of 1, 3 and 5 items were studied. The potentials are described in terms of scalp distribution, latency and amplitude, and are compared with behavioral descriptors of performance (accuracy and reaction time). These potentials are also compared with those evoked by an auditory target-detection task ('odd-ball' paradigm) in the same subject at the same session.

The potentials evoked by the probe stimuli consisted of a positive (P50–90), negative (N100–150), positive (P185–225) sequence in the first 250 msec, followed by a later, long-lasting (approximately 700 msec) positive component (labeled P3). This positivity consisted of an earlier component (latency of approximately 350–400 msec) with a frontal distribution, followed by a larger and later parietal component. The amplitude of the frontal component and the latency of the parietal component varied with the number of items in the memorized set differently from behavioral reaction times. Stimulus modality also affected both the amplitude and latency of the sustained parietal positive potential. Memory processes associated with the P3 complex in the 'odd-ball' task and the long-lasting positivity in the memory-scanning task are discussed.

**Key words:** Event-related potentials; Memory scanning; Stimulus modality; Task effect

The P300 (or P3) component of event-related potentials, evoked by the detection of a rare target stimulus (the so-called 'odd-ball' paradigm), is considered endogenous, reflecting cognitive processes such as stimulus evaluation and, in particular, aspects of memory function involved in 'mem-

ory updating' (Donchin 1981). The involvement of memory is based on systematic changes in P300 amplitude as a function of the target's global probability and the immediately preceding stimulus sequence (K.C. Squires et al. 1976). The target-detection task is not, however, specific to memory processes, since the accompanying evoked potentials may be unaffected in patients with profound memory deficits (K.C. Squires et al. 1980; Leppler and Greenberg 1984; Pfefferbaum et al. 1984; St. Clair et al. 1985; Starr and Barrett 1987; Patterson et al. 1988). In contrast, potentials evoked during the performance of a memory-scanning task were shown to be abnormal in patients with a specific disorder of auditory short-term memory, whereas in these same patients potentials

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in the target detection task were unaffected (Starr and Barrett 1987).

Several investigators have studied short-term memory processes using memory-scanning tasks originally described by Sternberg (1966, 1969, 1975) and correlated the electrophysiological data in normals with reaction time (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; Kramer et al. 1986; Starr and Barrett 1987). In this task individuals are asked to remember a short list of items, the memorized set, followed by a probe item. Subjects indicate whether the probe was or was not a member of the memorized set by making a choice reaction time (RT) response. The time required to 'scan' memory to make such a determination is linearly related to the number of items comprising the memory set. Separate functions relating RT and set size, and late potential latency and set size have been derived for the visual modality (Marsh 1975; Roth et al. 1975; Gomer et al. 1976; Adam and Collins 1978; Ford et al. 1979; Pfefferbaum et al. 1980; Kramer et al. 1986; Starr and Barrett 1987) and to a lesser extent for the auditory modality (Gaillard and Lawson 1984; Starr and Barrett 1987). Modality differences in memory scanning may be hypothesized since there is clinical evidence to suggest that auditory verbal and visual verbal short-term memory can be dissociated by specific brain lesions (Warrington and Shallice 1969; Saffran and Marin 1975; Shallice and Warrington 1977). Further, in the same patients auditory verbal and auditory non-verbal short-term memory may be differentially affected (Shallice and Warrington 1974), suggesting an additional distinction between verbal and non-verbal memory processes within the same modality.

The purpose of this study was to investigate memory scanning for digits presented in the auditory modality contrasted to digits in the visual modality, and in turn to compare these results to memory scanning of non-verbal auditory musical notes. The analysis of both behavioral and electrophysiological measures may serve to define the relationship of memory scanning for verbal items between the 2 modalities, and differences in scanning between verbal and non-verbal items. Mem-

ory-scanning potentials are also compared to the less memory-dependent auditory target-detection ('odd-ball') task.

## Methods

### *Subjects*

Eleven subjects, ranging in age between 18 and 45 years (average = 29, S.D. = 8), participated in the study. Subjects reported no neurological or hearing complaints and all had normal or corrected vision. The Mini-Mental State (Folstein et al. 1975) was administered to all subjects and no score fell below 29. Ten of the subjects were right handed.

### *Experimental paradigms*

*Memory-scanning tasks.* In a modified Sternberg memory-scanning paradigm (Starr and Barrett 1987), subjects were presented with a list of stimuli containing 1, 3 or 5 items to memorize. Following the memorized set, a probe stimulus was presented and subjects indicated whether or not the probe was a member of the memorized set by pressing with the fingers of the right hand one button to in-set (positive) probes and another button to out-of-set (negative) probes. Instructions stressed both speed and accuracy. The items presented were drawn from a repertoire of 9 possible stimuli including digits '1' through '9' for verbal auditory or visual presentations, and notes 'middle C' through 'D' one octave above for non-verbal auditory presentation. Notes consisted of a mixture of harmonics with the fundamental corresponding to a specific musical note, e.g., fundamental = 262 Hz for 'middle C' and 587 Hz for 'D' (one octave above). The probability that the probe was a member of the memorized set was 50%. The timing of the stimulus sequence following the signal to 'start' is shown in Fig. 1 for a trial with a 3-item memorized set. The items contained in each trial were presented in a pseudo-random fashion with the following restrictions: (1) the same probe item could not occur on 2 consecutive trials; (2) no more than 3 consecutive positive or negative probes occurred in sequence; and (3) the proportion of positive probes relative

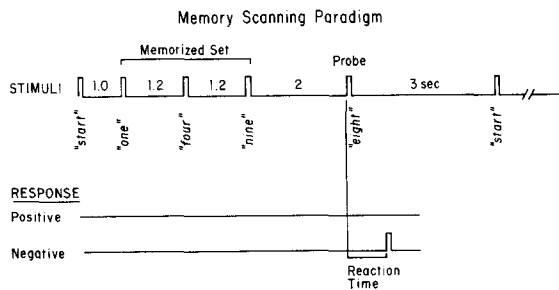


Fig. 1. Sample stimulus sequence in one trial of the memory-scanning task with 3 items in the memorized set. The 'stimuli' line contains pulses indicating the signal for the beginning of the trial ('start'), followed by the items to be memorized and the probe to be classified as positive (in-set) or negative (out-of-set). The temporal relationship of the items is given in seconds (sec). The occurrence of the button press is indicated in the lines labeled 'response,' and 'reaction time' is measured from probe onset. In this case the correct response was pressing the 'negative' button, as indicated.

to the position of the matching item in the memorized series (i.e., first, second, third, etc.) was adjusted to be equal.

In the visual presentation, both the digits and the word 'start' were displayed on a video monitor with a green phosphor screen. Individual display characters subtended a visual angle of 20" by 40" and were of sufficient contrast against the background for easy perceptibility. In the auditory presentation, the phonemic sequences comprising each digit, the notes, and the word 'start' were presented through earphones at an intensity of approximately 60 dB nHL. The time from stimulus onset to maximum intensity differed between the notes and the digits. Rise times were 10 msec for all notes and 15–110 msec for the digits, depending on the acoustic envelope of the specific digit. Stimulus durations were 100 msec for the notes and 500 msec for digits presented auditorily or visually. Stimulus generation, RT (+/- 10 msec resolution), and performance-accuracy measurements (percent correct responses) were conducted by a microcomputer (Acorn BBC, Model B) fitted with a speech synthesizer (for additional stimulus details see Starr and Barrett 1987).

**Auditory 'odd-ball' task.** Subjects listened to a series of 300 musical notes consisting of 'middle C' or 'C' one octave above. The order of the notes was random with the constraints that the higher

note occurred with a probability of 20% and that at least one low note separated consecutive high notes. The notes were presented through earphones at an interstimulus interval of 2 sec at an intensity of approximately 60 dB nHL. The duration of the notes was 100 msec. Subjects were instructed to press an RT button whenever the infrequent (higher) target note was sounded. Instructions stressed both speed and accuracy of performance.

### Procedures

**Testing session.** Following administration of a mental status questionnaire, electrodes were applied to the scalp and the subject was seated in a comfortable armchair inside a sound-attenuating chamber. Subjects were instructed on the tasks and told to relax facial musculature, fixate their gaze on the screen and avoid blinking during the trials.

The session started with the 'odd-ball' task followed by the memory-scanning tasks, in a sequence of auditory digits, visual digits and notes. For each type of stimulus, memorized sets and probes were presented in blocks of 20 trials with a fixed set size. For each stimulus type, 4 blocks of set size 1, 2 blocks of set size 3, and 4 blocks of set size 5 were presented. Thus, there were 80 probes for set sizes 1 and 5, and 40 probes for set size 3 for each of the 3 stimulus conditions. Before each condition, subjects were allowed a practice run.

**Performance analysis.** Behavior was analyzed in terms of speed and accuracy. The RTs to correctly identified probes that were free of eye movements during the sampled EEG epoch were averaged across trials of the same experimental condition. Trials with RTs exceeding 3 sec were considered incorrect responses. The percentage of correct responses in the total number of trials was calculated for each experimental condition. For each subject, there were 18 mean RTs for the memory-scanning tasks (3 stimulus conditions  $\times$  3 memorized set sizes  $\times$  2 probe types, positive or negative) and a single RT for the 'odd-ball' task. A corresponding number of accuracy measures were computed.

**Evoked potential recording and analysis.** Potentials were recorded from cup electrodes fixed

on the scalp at Fz, Cz and Pz, each referenced to linked electrodes on the earlobes. Eye movements were monitored by recording the potential difference between electrodes above and below the right eye. Potentials were differentially amplified ( $\times 200,000$  for the EEG;  $\times 100,000$  for the eye channel) using a bandpass of 0.1–100 Hz (3 dB down points, 6 dB/octave slopes). The potentials were sampled over a sweep time of 1.28 sec (dwell time = 5.0 msec) for probes, and 1.0 sec (dwell time = 3.9 msec) for the targets in the 'odd-ball' paradigm, beginning 120 msec before probe (or target) onset. Single-trial potentials were stored on disk for subsequent processing. Potentials were sampled, averaged and analyzed using a DEC MINC 11/23+ computer.

The single-trial evoked potentials of the memory-scanning task were sorted according to probe category (positive or negative), and only those potentials associated with correct responses without eye movements were included in the subsequent analysis and averaged. Eighteen averaged probe-evoked potentials were analyzed, corresponding to the 18 categories of behavioral measures. From the single trials of the 'odd-ball' paradigm, potentials evoked by the correctly detected target stimuli without eye movements were averaged. Measurements of peak amplitudes and latencies were performed on the filtered (zero phase shift, low-pass digital filter with a cut-off at 17 Hz) average wave form. Latencies were measured from stimulus onset, and amplitudes were measured relative to the mean voltage during the prestimulus baseline of 120 msec. Components were labeled according to polarity (P or N) and order of appearance (1, 2, 3, etc.) rather than approximate latency in milliseconds (e.g., P350). This was done because the latencies of homologous components could vary up to 50 msec between stimulus types and test conditions.

The P3 peak was defined as the maximum positivity in a given derivation, following the initial P1–N1–P2 sequence (see Fig. 2, Cz tracing to auditory digits). This criterion was also implemented in a computer program and applied to the recordings from each of the leads in some of the experimental conditions. In order to compare the manual and machine-scoring methods, the pro-

gram searched a pre-set time span for the maximum positivity. Correlations between the 2 scoring methods were high and differences were not significant. When present, differences between the manual and machine-scoring results clearly stemmed from deviant points that were not accounted for in the computer algorithm. The results detailed in this report are therefore based on manual measurements. The maximum positivity criterion was applied to recordings from each of the leads and resulted in the distinction of P3 into a frontal P3a and a later parietal P3b (Fig. 3).

#### *Statistical treatment of the data*

Group averages and standard deviations were computed for RT, percentage of correct responses, and the peak latencies and amplitudes of the evoked potentials. Analysis of variance procedures for repeated measures (stimulus type  $\times$  set size  $\times$  probe type (positive or negative)) were used to separately evaluate behavioral and evoked potential measures. The Newman-Keuls procedure was used to perform post-hoc comparisons of the means. Correlation and linear regression procedures were used to assess the relation between performance measures and set size, evoked potential measures and set size, and evoked potential measures and RT. The *t* statistic was used to test for slope (*b*) equal to zero, as well as for slope and intercept (*a*) differences between experimental conditions. Probabilities below 0.05 were considered significant.

## **Results**

### *Performance*

Accuracy was uniformly high for auditory and visual digits, whereas for notes there was a moderate loss in accuracy for the larger set sizes (Table I). Significant stimulus type  $\times$  set size ( $P < 0.001$ ) and stimulus type  $\times$  probe type ( $P < 0.007$ ) interactions were indicated. The first interaction was due to a lower percentage accuracy for notes than for auditory or visual digits, particularly in the larger set sizes (3 and 5). The second interaction indicated that response accuracy was essentially equivalent for positive probes among the 3 stimu-

TABLE I

Averages and standard deviations (S.D.) for performance accuracy in the different tasks. Accuracy is given as percentage of correct responses from the total number of trials presented. Tasks are designated by 3-character codes: A (auditory digits), V (visual digits) or T (notes) representing the 3 stimulus types; P (positive, in-set) or N (negative, out-of-set) indicating the type of probe; and 1, 3 or 5 for the size of the memorized set.

		Auditory digits					
		AP1	AN1	AP3	AN3	AP5	AN5
Average		96	97	97	99	96	98
S.D.		3	3	3	2	5	2
		Visual digits					
		VP1	VN1	VP3	VN3	VP5	VN5
Average		97	97	97	99	93	97
S.D.		2	3	3	3	6	3
		Musical notes					
		TP1	TN1	TP3	TN3	TP5	TN5
Average		97	89	89	75	82	72
S.D.		3	15	6	23	8	15

lus types, whereas accuracy for negative probes was lower for notes than either auditory or visual digits.

Reaction times were prolonged with increased set size (Table II). A significant stimulus type  $\times$  set size interaction was found ( $P < 0.001$ ) for RTs. For set sizes 3 and 5, RTs to notes were longer than to either auditory or visual digits; auditory digit RTs were longer than for visual digits, but

this difference was significant only with set size 3. There were no significant differences among the means for a set size of 1 for either notes, auditory digits or visually presented digits. Analysis of variance did not reveal any RT differences between positive and negative probes.

The functions relating RTs and set size (Table III) had slopes that were significantly different from zero. Slope differences between positive and

TABLE II

Averages and standard deviations (S.D.) of reaction times (msec) to probe stimuli in the different tasks. The tasks are designated by a 3-character code: A (auditory digits), V (visual digits) or T (notes) denoting stimulus type; correct P (positive, in-set) or N (negative, out-of-set) representing the probe type; and 1, 3 or 5 indicating the size of the memorized set.

		Auditory digits					
		AP1	AN1	AP3	AN3	AP5	AN5
Average		534	579	717	719	781	746
S.D.		82	103	124	88	146	109
		Visual digits					
		VP1	VN1	VP3	VN3	VP5	VN5
Average		484	542	624	620	689	684
S.D.		101	103	126	92	133	105
		Musical notes					
		TP1	TN1	TP3	TN3	TP5	TN5
Average		530	575	884	946	937	1057
S.D.		130	152	321	277	172	271

TABLE III

Correlation coefficients ( $r$ ) and linear regression intercepts ( $a$ ) in msec and slopes ( $b$ ) in msec/item for reaction time (to correctly classified probes) as a function of the number of items in the memorized set. The value of the  $t$  statistic and associated probability ( $P$ ) are also indicated. The types of tasks are represented by 2-letter codes: A (auditory digits), V (visual digits) or T (notes), followed by an indication of whether the probe was positive (P) or negative (N).

	Auditory digits		Visual digits		Musical notes	
	AP	AN	VP	VN	TP	TN
$r$	0.65	0.58	0.58	0.52	0.60	0.64
$a$	492	554	445	509	478	497
$b$	62	43	51	35	102	121
$t$	4.76	3.99	4.00	3.37	4.13	4.63
$P$	< 0.001	< 0.001	< 0.001	0.002	< 0.001	< 0.001

negative probes were not significant for any of the stimulus types. Intercepts for negative probes were slightly higher than to positive probes but these differences were not significant.

Since no significant slope or intercept differences between probe types were found, positive and negative probes were pooled for stimulus-type comparisons. Pooled RT/set size slopes were 52, 43 and 111 msec/item for auditory digits, visual digits and notes, respectively. The RT/set size slopes for both auditory and visual digits were significantly less steep than the slope for notes ( $P < 0.005$  and  $P < 0.001$ , respectively). Pooled RT/set size intercepts were 523, 477 and 488 msec, respectively, for auditory digits, visual digits and notes. Intercept differences between stimulus types were not significant.

#### Evoked potentials

**Component definition.** Fig. 2 presents the wave forms of the potentials evoked by the probe items averaged across subjects and set sizes for the 3 types of stimuli. All wave forms began with a

P1–N1–P2–N2 sequence of peaks with average vertex latencies for auditory digits of 96 (P1), 162 (N1), 235 (P2) and 304 (N2) msec, respectively; for visual digits the latencies were 87 (P1), 138 (N1), 219 (P2) and 284 (N2); and for notes the latencies were 56 (P1), 110 (N1), 187 (P2) and 259 (N2) msec. Following the P1–N1–P2–N2 sequence, 2 prominent positivities were recorded: an earlier (350–400 msec latency) transient, frontal component (called P3a), which was superimposed in the central and parietal leads on a sustained (> 700 msec) positivity (called P3b). The peak of P3a was clearly identified with little latency variability in the Fz recordings, whereas the peak of P3b varied in latency (see Fig. 3 for individual examples). Evoked potential wave forms to probes were clearly detectable across stimulus types (see Fig. 4; note that the latency marks on these grand averages are placed at the mean latency across subjects rather than at the peak of the grand average) and across individual subjects (Fig. 5).

The latencies and amplitudes of components P1 through N2 differed as a function of stimulus type but not set size (see Fig. 4). No significant relationships between set size and component latency or amplitude were indicated for peaks P1 through N2. In contrast, the P3 component varied for both stimulus type and set size (Fig. 4 and Table IV). Note, in Table IV, the relatively constant peak latency of P3a across set sizes, whereas P3b latency increased as a function of the number of items in the memorized set.

**P3a component.** Analysis of variance revealed significant overall stimulus type ( $P < 0.001$ ) and

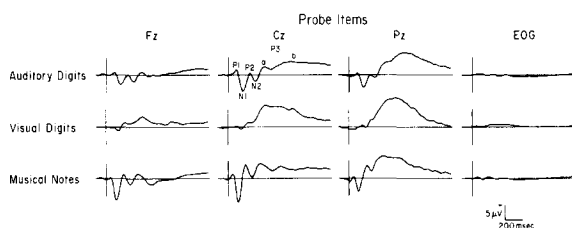


Fig. 2. Evoked potentials across subjects and across sizes of memorized sets to combined positive and negative probes for the 3 presentation modes used in this study.

set size ( $P < 0.001$ ) effects for the amplitude of P3a. Amplitudes of P3a were larger for the visual than either auditory or note presentations, and largest for a set size of 1 compared to set sizes of 3 and 5. A stimulus-type effect ( $P < 0.001$ ) for P3a latency indicated longer latencies to auditory digits than to either notes or visual digits. Only the latency differences between auditory digits and notes attained significant levels. A significant

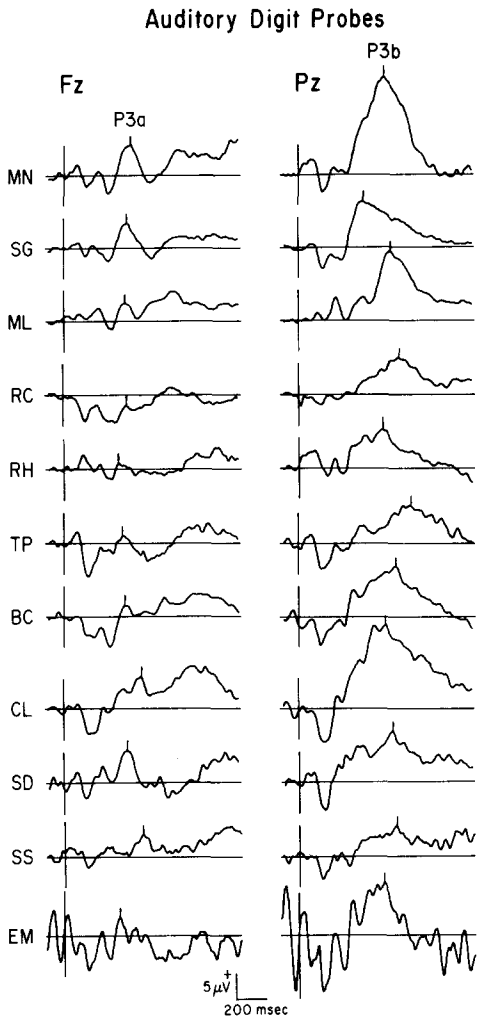


Fig. 3. Individual evoked potentials for each subject to the probes following 1-item memorized sets of auditory digits to correct responses to the negative probes. The potentials recorded at Fz and Pz are presented with vertical tick marks indicating the points at which P3a and P3b were measured.

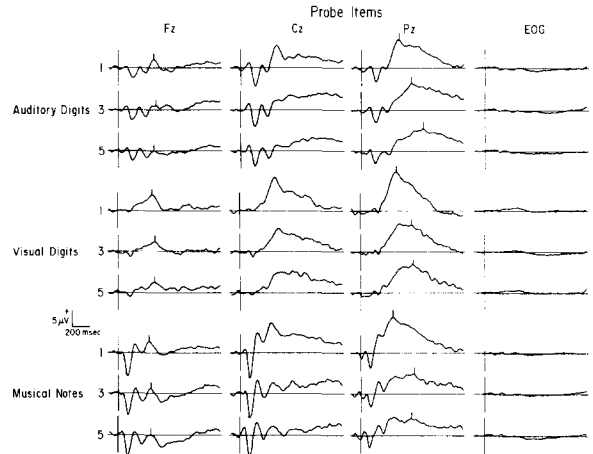


Fig. 4. Evoked potentials to the correctly identified positive probes averaged across subjects to the different memory-scanning tasks used in this study. The stimulus type and memorized set size are indicated to the left of the respective wave forms. The vertical tick marks in the Fz and Pz derivations are placed at the mean latencies across subjects for P3a and P3b, respectively. See Fig. 3 for the relative variability of these measures across subjects in the 1-item auditory digit task.

probe-type effect ( $P < 0.02$ ) indicated that the latencies of P3a were shorter to positive than to negative probes (approximately 10 msec).

**P3b component.** The latency of P3b showed significant stimulus-type ( $P < 0.001$ ) and set size ( $P < 0.001$ ) effects. P3b latencies to auditory digits were longer than either visual digits or notes. The latency differences between P3b to visual digits and to notes did not reach statistical significance. P3b latencies to set sizes of 3 and 5 were significantly longer than to a set size of 1, but not from each other. The amplitudes of P3b were affected by a significant ( $P < 0.01$ ) stimulus type  $\times$  set size interaction. The amplitudes of P3b were generally larger across set sizes for the visual presentation of digits. Post-hoc comparisons indicated that at set size 1, amplitudes to visual digits were larger than to auditory digits, at set size 3 none of the P3b amplitude differences attained significance, and at set size 5 amplitudes to visual digits were larger than those evoked by notes. There was some indication of an overall effect of probe type on latency (latencies to negative probes longer by 32 msec) but this effect was not significant ( $P = 0.07$ ).



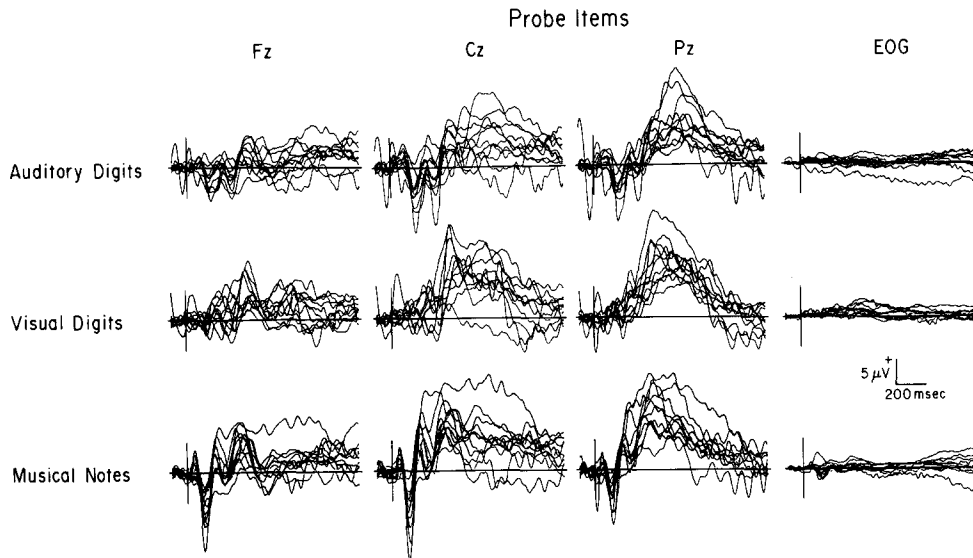


Fig. 5. Superimposed averages to correctly identified positive probes following memorized sets with 3 items from individual subjects.

#### *EP correlates of set size and performance*

*Correlates of set size.* Potentials evoked by the probes changed with memorized set size (Fig. 4), with both the latencies of P3b and the amplitudes of P3a (except one instance) correlated with set size and having slopes significantly different from zero (Table V). P3b amplitudes were correlated with set size only when notes were being scanned in memory.

Slope and intercept differences between potentials to positive and negative probes were not significant for any of the stimulus types. Consequently, values for positive and negative probes were pooled for stimulus-type comparisons. Table VI summarizes the resulting correlations, slopes and intercepts. The slopes of the functions relating P3a and P3b latencies and amplitudes with set size were not significantly different between stimulus types (auditory digits, visual digits, notes), with the exception of a P3b amplitude/set size slope for notes which was steeper than for both auditory ( $P < 0.03$ ) and visual digits ( $P < 0.05$ ). The intercepts of the functions relating P3a latency with set size were significantly shorter for notes than auditory and visual digits ( $P < 0.0001$  and  $P < 0.01$ , respectively). For P3a amplitude, the intercept for auditory digits was smaller than for visual digits ( $P < 0.01$ ). For P3b latency the intercept for audi-

tory digits was longer than for both visual digits and notes ( $P < 0.01$  and  $P < 0.01$ , respectively). For P3b amplitude, intercept differences between stimulus types were not significant.

The slopes of RT as a function of set size were steeper than the slopes of P3b latency with set size for auditory digits ( $P < 0.05$ ) and notes ( $P < 0.001$ ), and this difference approached significance ( $P < 0.1$ ) for visual digits (see Fig. 6). The corresponding intercept differences between RT and P3b latency were not significant for any of the stimulus types.

*Correlates of performance.* Both P3a and P3b amplitudes, as well as P3b latencies, in the majority of instances, were correlated with RT with slopes significantly different from zero, whereas P3a latencies were not related to RT (Table VII). Since slope and intercept differences between the potentials to positive and negative probes were not significant for any of the stimulus types, positive and negative probes were pooled for stimulus-type comparisons. Table VIII summarizes the resulting correlations, slopes and intercepts. The slopes of the functions relating latencies and amplitudes of P3a and P3b with RT were not different between stimulus types (auditory digits, visual digits, notes), except for a marginally steeper ( $P = 0.051$ ) P3a amplitude/RT slope for auditory digits

TABLE IV

Averages (Ave) and standard deviations (S.D.) of peak latencies and amplitudes for P3a (Fz) and P3b (Pz) evoked by probes in the various tasks. Latencies (lat.) are in msec and amplitudes (amp.) are in  $\mu\text{V}$ . The tasks are designated by 3-character codes: A (auditory digits), V (visual digits) or T (notes) representing the 3 stimulus types; P (positive) or N (negative) indicating the probe type; and 1, 3 or 5 indicating the size of the memorized set.

			Auditory digits					
			AP1	AN1	AP3	AN3	AP5	AN5
P3a (Fz)	lat.	Ave	395	406	405	428	403	407
		S.D.	26	42	39	36	27	37
	amp.	Ave	3.47	3.48	2.47	0.78	1.02	-0.25
		S.D.	2.47	2.46	3.37	2.32	2.46	2.58
P3b (Pz)	lat.	Ave	556	592	631	684	667	709
		S.D.	136	78	111	127	82	108
	amp.	Ave	10.81	11.38	11.80	10.84	9.76	9.97
		S.D.	3.64	4.45	3.97	5.18	4.08	4.79
			Visual digits					
			VP1	VN1	VP3	VN3	VP5	VN5
P3a (Fz)	lat.	Ave	392	401	372	418	390	381
		S.D.	58	48	46	88	62	69
	amp.	Ave	6.47	6.69	4.64	3.56	4.88	3.31
		S.D.	2.63	3.34	2.21	2.20	2.43	2.73
P3b (Pz)	lat.	Ave	459	506	512	554	563	595
		S.D.	87	76	98	88	90	72
	amp.	Ave	14.25	13.83	11.60	12.54	11.69	13.27
		S.D.	4.54	4.12	4.31	4.83	3.25	4.84
			Musical notes					
			TP1	TN1	TP3	TN3	TP5	TN5
P3a (Fz)	lat.	Ave	352	353	358	357	356	356
		S.D.	28	19	25	32	30	53
	amp.	Ave	4.53	6.65	2.43	0.95	0.71	1.02
		S.D.	3.38	3.20	2.66	2.88	3.75	3.44
P3b (Pz)	lat.	Ave	473	438	573	603	587	628
		S.D.	128	96	152	115	179	122
	amp.	Ave	14.04	13.04	9.35	9.63	8.34	7.79
		S.D.	5.01	4.96	3.65	5.77	5.42	3.46

compared to notes. None of the P3a or P3b latency and amplitude/RT intercept differences between stimulus types were significant except for longer P3a latency/RT intercepts for visual digits compared to notes ( $P < 0.05$ ).

#### Target-detection ('odd-ball') task

The average RT for the target-detection task was 361 msec (S.D. = 107 msec) and the average accuracy was 99% (S.D. = 1). The evoked potentials to the correctly identified target stimuli are presented in Fig. 7. The wave forms began with a P1 (56 msec), N1 (112 msec), P2 (175 msec), N2

(225 msec) sequence, followed by a frontal P3a (average latency = 331 msec, S.D. = 18; average amplitude = 5.13  $\mu\text{V}$ , S.D. = 4.54) and a central-parietal P3b (average latency = 424 msec, S.D. = 73; average amplitude = 9.77  $\mu\text{V}$ , S.D. = 8.42).

#### Discussion

The results of this study on normal young adults, recording both event-related potentials and behavior during memory scanning, showed that the slopes and intercepts of reaction time as a

TABLE V

Correlation coefficients ( $r$ ) and linear regression intercepts ( $a$ ) and slopes ( $b$ ) for P3a (Fz) and P3b (Pz) latency (lat.) and amplitude (amp.) as a function of the number of items in the memorized set. Intercepts are in msec for latencies and  $\mu\text{V}$  for amplitudes, slopes are in msec/item for latencies and  $\mu\text{V}/\text{item}$  for amplitudes. The values of the  $t$  statistic and associated probability ( $P$ ) are indicated. Tasks are designated by 2-character codes: A (auditory digits), V (visual digits) or T (notes) for the different stimulus types; and P (positive) or N (negative) indicating the probe types.

		Auditory digits		Visual digits		Musical notes				
		AP	AN	VP	VN	TP	TN			
P3a (Fz)	lat.	$r$	0.10	0.02	-0.02	-0.12	-0.02	-0.08		
		$a$	395	412	386	415	353	353		
		$b$	1.82	0.45	-0.57	-4.89	0.91	0.91		
		$t$	0.55	0.11	0.10	-0.65	0.31	0.23		
	amp.	$r$	-0.35	-0.54	-0.26	-0.45	-0.45	-0.57		
		$a$	4.16	4.14	6.53	7.07	5.42	6.93		
		$b$	-0.61	-0.93	-0.40	-0.84	-0.95	-1.37		
		$t$	2.09	3.58	1.53	2.80	2.76	3.76		
		$P$	0.04	0.001	0.14	0.01	0.01	0.001		
		P3b (Pz)	lat.	$r$	0.39	0.42	0.43	0.43	0.34	0.58
				$a$	535	574	434	485	459	414
				$b$	28	29	26	22	29	48
$t$	2.34			2.59	2.69	2.69	1.75	3.88		
amp.	$r$		-0.11	-0.12	-0.26	-0.05	-0.47	-0.46		
	$a$		11.58	11.79	14.44	13.63	14.84	14.08		
	$b$		-0.76	-0.35	-0.64	-0.14	-1.42	-1.31		
	$P$		0.53	0.49	0.15	0.78	0.009	0.015		

TABLE VI

Linear regression intercepts ( $a$ ) and slopes ( $b$ ) for P3a (Fz) and P3b (Pz) latency (lat.) and amplitude (amp.) as a function of the number of items in the memorized set for combined positive and negative probes. Intercepts are in msec for latencies and  $\mu\text{V}$  for amplitudes, slopes are in msec/item for latencies and  $\mu\text{V}/\text{item}$  for amplitudes.

		Auditory digits	Visual digits	Musical notes	
P3a (Fz)	lat.	$r$	0.05	-0.07	0.05
		$a$	404	401	353
	amp.	$b$	1.1	-2.7	0.9
		$r$	-0.44	-0.36	-0.50
		$a$	4.2	6.8	6.2
		$b$	-0.8	-0.6	-1.2
P3b (Pz)	lat.	$r$	0.40	0.42	0.42
		$a$	555	460	436
	amp.	$b$	28.5	24.1	38.1
		$r$	-0.12	-0.15	-0.44
		$a$	11.7	14.0	14.5
		$b$	-0.3	-0.4	-1.4

function of memorized set sizes are in general agreement with previous studies using visual stimuli (Sternberg 1966; Marsh 1975; Roth et al. 1975; Adam and Collins 1978; Ford et al. 1979; Karrer et al. 1980) as well as auditory and visual stimuli (Starr and Barrett 1987). Smaller values for RT slopes reported by some studies (Burrrows and Murdock 1969; Gomer et al. 1976) may be due to procedural differences. In the present experiments, the RT slope for notes was approximately twice that of the slopes for digits. The use of notes in this memory-scanning task has not been previously reported, and the accompanying steeper slope may reflect a property of non-verbal memory processes. This suggestion gains support by similarly steep slopes obtained for RTs in memory scanning of nonsense syllables (Gaillard and Lawson 1984).

The event-related potentials accompanying the recognition of the memorized items showed a gen-

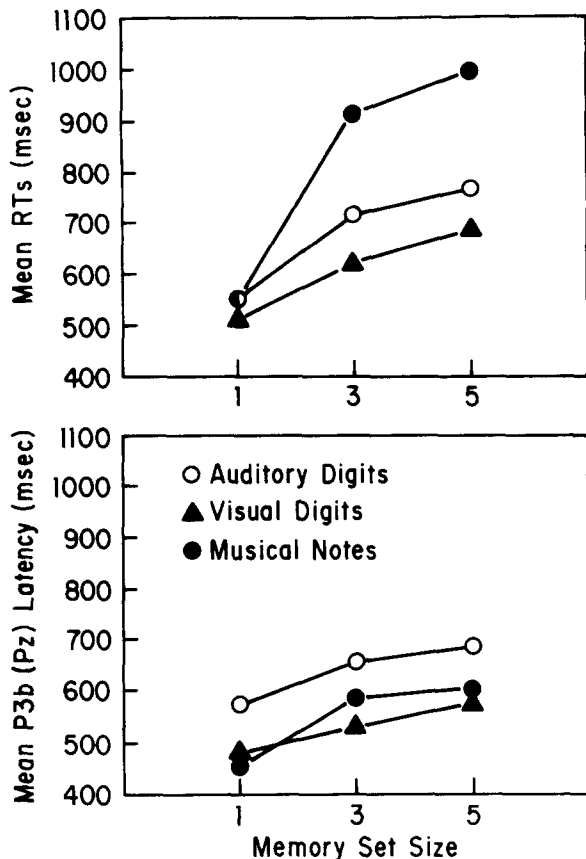


Fig. 6. Comparison of reaction times (top) and P3b (Pz) latencies (bottom) as a function of memorized set size (pooled across correct responses to positive and negative probes). See Tables III and V for quantification of these slopes.

eral common feature of a sustained long-latency scalp positive component with frontal and parietal constituents. Almost without exception, earlier studies using verbal stimuli presented visually obtained a parietal positive component that increased in latency with increasing set size (Gomer et al. 1976; Adam and Collins 1978; Ford et al. 1979; Karrer et al. 1980; Starr and Barrett 1987). The rate of latency increase was approximately half that of RT, in agreement with the findings of the present study. Most studies have not differentiated the positive component into 2 constituents. One study (Adam and Collins 1978) reported 2 components measured at Cz (P270, P350) which increased in latency with set size, but did not use a

frontal recording electrode so that identification of the earlier peak with P3a is uncertain. Another study (Starr and Barrett 1987) noted the frontal and parietal constituents but did not report the effect of set size on the frontal component. It appears that amplitudes of the sustained positivity are reduced with increasing set size (Marsh 1975; Gomer et al. 1976; Karrer et al. 1980; Starr and Barrett 1987) in agreement with our findings.

The 2 studies using auditory stimuli in a memory-scanning task reported conflicting results. Gaillard and Lawson (1984) used monosyllables and reported that the sustained positive component decreased in amplitude without a change in latency as a function of increasing set size. In contrast, Starr and Barrett (1987) reported a latency increase without an amplitude effect when auditory verbal stimuli were used. This difference between studies may, in part, be resolved if frontal and parietal positive components are distinguished. We found the frontal P3a to decrease in amplitude with set size (similar to the first study) whereas the parietal P3b component increased in latency (similar to the second study). The use of consonant-vowel meaningless monosyllables in the first study (Gaillard and Lawson 1984) probably also contributed to the difference. In the present study, for instance, P3b amplitude to non-verbal items (i.e., musical notes) decreased with set size in a manner similar to that of the nonsense monosyllables used by Gaillard and Lawson.

Memory-scanning studies analyzing RT data have suggested that the entire memorized set is compared with the probe item before the response is made, i.e., that scanning is exhaustive (Sternberg 1966, 1969). The nature of this comparison has been in controversy, with some (e.g., Sternberg 1975) supporting a serial process (i.e., one item at a time), while others (e.g., Atkinson et al. 1969) favor a parallel comparison. Still others prefer a parallel comparison that is not exhaustive but self-terminating if a match is detected (Ratcliff 1978). These conflicting models for memory scanning have been reconciled by a 2-stage model with serial decoding from memory followed by parallel comparison (Corballis 1979). It is of interest to consider how the neural events underlying the potentials evoked by the probes in this task may

TABLE VII

Correlation coefficients ( $r$ ) and linear regression intercepts ( $a$ ) and slopes ( $b$ ) for P3a (Fz) and P3b (Pz) latency (lat.) and amplitude (amp.) as a function of reaction time. Intercepts are in msec for latencies and in  $\mu\text{V}$  for amplitudes. Slopes are EP latency vs. RT latency (msec/msec) and  $\mu\text{V}/\text{msec}$  for amplitudes. The values of the  $t$  statistic and associated probability ( $P$ ) are indicated. Tasks are designated by 2-character codes: A (auditory digits), V (visual digits) or T (notes) for the different stimulus types; and P (positive) or N (negative) indicating probe type.

		Auditory digits		Visual digits		Musical notes		
		AP	AN	VP	VN	TP	TN	
P3a (Fz)	lat.	$r$	0.27	0.30	-0.19	0.03	0.34	-0.01
		$a$	366	349	428	389	330	354
		$b$	0.05	0.10	-0.07	0.02	0.03	-0.001
		$t$	1.55	1.76	1.10	0.17	2.01	0.06
		$P$	0.13	0.09	0.28	0.87	0.053	0.95
	amp.	$r$	-0.50	-0.51	-0.25	-0.50	-0.32	-0.37
		$a$	8.52	9.52	7.89	12.95	5.66	6.90
		$b$	-0.01	-0.01	-0.00	-0.01	-0.00	-0.00
		$t$	3.20	3.29	1.44	3.19	1.85	2.19
		$P$	0.003	0.002	0.16	0.003	0.07	0.04
P3b (Pz)	lat.	$r$	0.42	0.58	0.39	0.30	0.22	0.61
		$a$	403	284	352	415	446	324
		$b$	0.32	0.55	0.26	0.22	0.12	0.27
		$t$	2.59	4.01	2.37	1.73	1.28	4.33
		$P$	0.01	< 0.001	0.02	0.09	0.21	< 0.001
	amp.	$r$	-0.29	-0.41	-0.46	-0.44	-0.38	-0.48
		$a$	15.56	21.48	20.24	23.89	16.13	16.98
		$b$	-0.01	-0.02	-0.01	-0.02	-0.01	-0.01
		$t$	1.67	2.48	2.84	2.71	2.31	3.06
		$P$	0.10	0.02	0.008	0.01	0.03	0.004

be related to the stages contained in these various models of memory scanning. In this discussion, 'memory scanning' is used in its most general sense, which in some models may include both the

decoding and comparison stages (e.g., Corballis 1979).

If an event-related component reflected scanning of memory, the slope of component latency

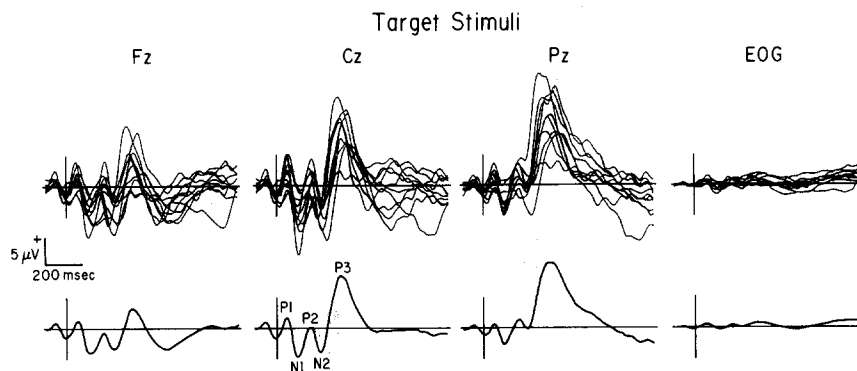


Fig. 7. Evoked potentials to the target stimuli in the 'oddball' detection task. The individual wave forms for each subject are shown superimposed (top) and averaged across subjects (bottom). Note that the sweep time for this figure is 1000 msec compared to the 1280 msec used in the other figures.

TABLE VIII

Linear regression intercepts (*a*) and slopes (*b*) for P3a (Fz) and P3b (Pz) latency (lat.) and amplitude (amp.) as a function of reaction time, for combined positive and negative probes. Intercepts are in msec for latencies and  $\mu\text{V}$  for amplitudes, slopes are EP latency vs. RT latency (msec/msec) and  $\mu\text{V}/\text{msec}$  for amplitudes.

			Auditory digits	Visual digits	Musical notes
P3a (Fz)	lat.	<i>r</i>	0.28	-0.07	0.14
		<i>a</i>	360	413	343
		<i>b</i>	0.07	-0.03	0.01
	amp.	<i>r</i>	-0.50	-0.37	-0.34
		<i>a</i>	8.8	9.8	6.2
		<i>b</i>	-0.01	-0.01	-0.004
P3b (Pz)	lat.	<i>r</i>	0.48	0.36	0.41
		<i>a</i>	362	375	383
		<i>b</i>	0.4	0.2	0.2
	amp.	<i>r</i>	-0.34	-0.43	-0.44
		<i>a</i>	17.8	21.6	16.6
		<i>b</i>	-0.01	-0.01	-0.01

as a function of memorized set size would be equal for positive and negative probes, but would not necessarily be equal to the corresponding RT slope, because additional serial stages of comparison and response selection follow scanning. On the other hand, if a component reflected both the processes of scanning and response selection, and those processes were serial and exhaustive, component latency would change with set size with the same slope as RT, and the component's intercept (equivalent to a set size of zero) would represent the duration of the motor part of the task. Further, if these processes were self-terminated when a match was made, responses to negative probes would entail a scan of the entire memorized set, whereas responses to positive probes would be selected when a match between probe and set item was found. Given the random position of the matching item in the set, this match would occur, on the average, halfway through scanning the memorized set. Thus, the slope relating component latency to set size for positive probes would be approximately half that of the negative probes. Observing Tables III and V, the slopes of P3b latency are significantly correlated with set size and are similar for positive and negative probes. Latency slopes are somewhat over half of the

corresponding RT slopes for the digit presentations (A and V) and about a third for the notes (T). The overall latency difference between potentials to positive and negative probes was small (approximately equal to the scanning time of a single item) and only marginally significant ( $P = 0.07$ ) and, therefore, did not support the concept that scanning was self-terminating when identifying positive probes. The P3b latency slope differences between positive and negative probes were not significant for any of the stimulus types. Thus, these data suggest that P3b reflects neural processes associated with a serial scanning of the memorized set prior to response selection. They further suggest that there is no difference in this serial scanning prior to response to positive compared with negative probes. Similar conclusions have been suggested by others (e.g., Ford et al. 1979).

The approximate doubling of the slope of the RTs to non-verbal (notes) compared to verbal (digits) stimuli suggests additional serial processing for the non-verbal comparisons. One possible explanation is that the notes were recoded to another dimension, i.e., possibly verbally (for example, 'high,' 'less high,' 'slightly low,' 'low,' etc.), prior to response selection. If this explanation is correct, P3b cannot reflect this recoding because, unlike RT, P3b latency slope as a function of set size is not significantly steeper for notes than for verbal stimuli (cf., Table III and Tables V and VI). The significantly longer P3 latencies to auditory digits, compared to notes, which would seem to contradict this suggestion, are most probably due to differences in the rise times of the acoustic stimuli being on the average up to 50 msec longer to the digits than to the notes. This interpretation is supported by the finding of a similar magnitude of latency differences in the early peaks, beginning with P1 through N2, of the evoked potentials to these 2 types of auditory stimuli.

The P3 component evoked by target stimuli in the 'odd-ball' paradigm (P300) has been implicated in memory updating (Donchin 1981; K.C. Squires et al. 1976). However, the finding of a normal latency P3 in certain patients with memory impairments secondary to herpes encephalitis (K.C. Squires et al. 1980), Alzheimer's disease and

Korsakoff's syndrome (Pfefferbaum et al. 1984; St. Clair et al. 1985; Patterson et al. 1988), mild arteriosclerotic dementia (Leppler and Greenberg 1984) and in a group of patients with a specific disorder of auditory short-term memory (Starr and Barrett 1987), suggests that the memory aspects of the target-detection task may not be the major cognitive attribute contributing to the resulting parietal positivity (P300). A comparison of P3 in the 'odd-ball' task with the sustained positivity that accompanied memory scanning in this study reveals several differences. The duration of the 'odd-ball' P3 was approximately half that of the P3 obtained in the memory-scanning task (300 vs. 700 msec), and the amplitude, when compared to probes following notes in a 1-item memorized set, was consistently smaller (9.7 vs. 14.9  $\mu\text{V}$ , respectively). One possible explanation accounting for this amplitude difference might involve the contingent negative variation (CNV) occurring during the performance of the memory-scanning task (e.g., Roth et al. 1975). A CNV may develop in the interval between the last item of the memorized set and the probe's appearance. The positive going resolution of the CNV may coincide with the appearance of the probe resulting in an apparent increase in the amplitude of P3. However, with the system high-pass used in this study (0.1 Hz), or even with a lower value (0.01 Hz, Starr and Barrett 1987), we did not detect a CNV. We did not use a warning signal to indicate the probe's appearance, as did Roth and his colleagues, which may account for the differences in CNV detectability.

Another explanation to account for the differences between the positive P3 components to these 2 tasks might be differences in the demands of the 2 tasks. In the 'odd-ball' task, the comparison of the stimulus is with a fixed item which is the same throughout the session. This comparison is easily performed. In contrast, in memory scanning the comparison is with a new memorized set on each trial. The more demanding nature of the memory-scanning task, compared to target detection, is also supported by the RT measures. For example, RTs to notes in a 1-item set size were approximately 200 msec longer than RTs to notes as targets in the 'odd-ball' task. Thus, the larger

amplitudes of P3 in memory scanning relative to the 'odd-ball' task may, in part, reflect the contribution of task demands. Alternatively, the parietal positivity evoked in these 2 tasks might entail activity in distinct neural systems having different amplitude distributions over the scalp.

The memory-scanning tasks of the present study clearly demonstrated distinct late positive peaks, P3a and P3b (Figs. 2, 3 and 4) for the 3 types of stimuli tested. In contrast, these components in the 'odd-ball' task are sometimes overlapping and difficult to distinguish. Our memory-scanning results on the frontal positivity resemble the P3a of the 'odd-ball' task and are compatible with its proposed association with arousal independent of an overt response (N.K. Squires et al. 1975), since P3a latencies were not associated with set size. Our results on the sustained parietal positivity, which increased in latency with set size, resemble the P3b of the 'odd-ball' task, which increases in latency with task demands, suggesting that both are more intimately associated with response selection than is P3a (see Pritchard 1981). The relative independence of response selection and execution, suggested in the present study to explain the differences in slopes of RT and the latency of the parietal positivity, has also been suggested in connection with the 'odd-ball' P3b (N.K. Squires et al. 1977; Magliero et al. 1984; McCarthy and Donchin 1981). However, the parietal positivity recorded in the memory-scanning task is specifically associated with scanning of memory prior to response selection, whereas the P3b in the 'odd-ball' task may be related to 'memory updating' (Donchin 1981) and not to a scanning of the contents of memory.

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