Title
Readiness to respond in a target detection task: pre- and post-stimulus event-related potentials in normal subjects

Journal
Clinical Neurophysiology, 96(1)

ISSN
1388-2457

Authors
Starr, A
Sandroni, P
Michalewski, HJ

Publication Date
1995

DOI
10.1016/0013-4694(94)00162-e

ELSEVIER

Electroencephalography and clinical Neurophysiology 96 (1995) 76–92

Readiness to respond in a target detection task: pre- and post-stimulus event-related potentials in normal subjects

A. Starr *, P. Sandroni and H.J. Michalewski

Department of Neurology, University of California, Irvine, CA 92717 (USA)

(Accepted for publication: 1 June 1994)

Summary Brain potentials were recorded from 12 normal subjects engaged in an auditory target detection task (target stimulus probability of 0.2, stimulus rate of 1 every 2 sec) when instructions were (1) to press a response button with the thumb of the dominant hand to each target or (2) to keep a mental count of each target. A pre-stimulus slow negative potential was identified before every stimulus except non-targets immediately after targets. The amplitude of the pre-stimulus negativity was significantly affected by task instructions and was up to 4 times larger during the button press than the mental count condition. In contrast, the amplitudes and latencies of the event-related components (N100, P200, N200 and P300), when slow potentials were removed by filtering, were not different as a function of press or count instructions. The immediately preceding stimulus sequence affected both the amplitude and onset latency of the pre-stimulus negativity; both measures increased as the number of preceding non-targets increased. The amplitude of the pre-stimulus negative shift to targets also increased significantly as RT speed decreased. The major portion of the pre-stimulus negative potential is considered a readiness potential (RP) reflecting preparations to make a motor response. The amplitude of the RP during the target detection task did not significantly lateralize in contrast to the RP accompanying self-paced movements.

Keywords: Readiness potentials; Target detection; Event-related potentials; Reaction time; P300

The target detection or "odd-ball" task requires a subject to detect the presence of a target signal occurring infrequently and randomly in a train of otherwise identical signals (Sutton et al. 1965; Picton 1992). A positive potential accompanies the target stimulus of largest amplitude in the mid-parietal region with a peak latency of approximately 300 msec (the "P300"). The P300 in the target detection task is considered a marker of "cognitive" brain events as varied as "memory updating" (Donchin and Coles 1988) and the resolution of "expectancy" (Verleger 1988).

The latency of P300 increases with subject age (Goodin et al. 1978; Pfefferbaum et al. 1984; Polich et al. 1985), task difficulty (Goodin et al. 1983), target probability (Tueting et al. 1970) and can be abnormally slowed in dementing disorders (Goodin et al. 1978). In both normal (Michalewski et al. 1986) and demented subjects (Patterson et al. 1988) P300 latency varies considerably from trial to trial whereas the latencies of sensory components, N100 and P200, have less variability. When tasks that evoke a P300 are combined with the requirement to make a motor response to the targets for reaction time measures (RT), the latency of P300 can be correlated with RT (Ritter et al. 1972; Kutas et al. 1977; Roth et al. 1978). In these circumstances, the brain processes underlying both P300 generation and motor responses appear closely related. However, when the demands of motor performance (Ragot and Renault 1981) and/or cognitive processing (Duncan-Johnson and Kopell 1981) pose additional constraints, RT and P300 latency become disassociated (Donchin and Coles 1988).

There is disagreement on whether brain activity preceding the target stimulus in the target detection task influences P300 measures (see Deecke and Lang 1988; Donchin and Coles 1988). The dispute is compounded by the variety of slow negative potential shifts identified in experimental situations requiring movements or target stimulus identification (see McCallum 1988, for review). One of these potentials, the "readiness potential" (RP), is a sustained negative potential shift that appears when subjects make repetitive self-paced movements without a stimulus cue (Kornhuber and Deecke 1965). The potential appears several seconds before the motor response and is largest over central leads. In the period close to movement onset, the potential becomes larger over motor cortex contralateral than ipsilateral to the responding limb (Deecke et al. 1969; Kutas and Donchin 1980; Barrett et al. 1986).

* Corresponding author. Tel.: +1 (714) 8566088; Fax: +1 (714) 7252132.

SSDI 0013-4694(94)00162-E

EEP 93219

A second negative potential, the "contingent negative variation" (CNV), is a sustained negative potential that appears when subjects are forewarned by one stimulus (S1) that a subsequent stimulus (S2) is imminent (Walter et al. 1964). A negative shift develops at the S1 stimulus, gradually increases in amplitude until the S2 stimulus, when the potential returns to baseline or becomes positive. The CNV appears even in the absence of a requirement for a motor response to the S2 stimulus and is thus distinguished from the RP which, by definition, requires a movement (Ruchkin et al. 1986). The scalp distribution of the CNV is largest centrally without significant lateralization. However, several studies (Rohrbaugh et al. 1976, 1980; Ritter et al. 1980; Rohrbaugh and Gaillard 1983) have suggested that the CNV is comprised of at least 2 separate potentials: an initial component at the time of S1 with a scalp distribution that varies with stimulus modality and a second component at the time of S2 of largest amplitude centrally independent of stimulus modality representing motor preparation (i.e., a readiness potential).

A third pre-stimulus negative potential, the "stimulus preceding negativity" (SPN, Brunia and Damen 1988; Lang et al. 1988) appears several hundred msec before a stimulus that is to be evaluated for response selection and varies in scalp distribution depending on the cognitive demands of the task.

The correlation between pre-stimulus slow potential amplitudes and motor behavior varies. In the S1-S2 paradigm, the correlations, when present, show that the amplitude of CNV is inversely related to RT (Hillyard and Galambos 1967; Rebert and Tecce 1980). The amplitude of the RP in self-paced movements does correlate with the force of the movement (Kristeva et al. 1990) as well as the discreteness of the movement (Kitamura et al. 1993). The identification of slow potential shifts in experiments utilizing continuous stimulus presentation are few (e.g., Tueting and Sutton 1973; Donchin et al. 1975; McCallum 1988; Ortiz et al. 1993). Coles et al. (1988) have employed choice reactions in a S1-S2 paradigm relating the extent of lateralization of RP and the choice of limb making a motor response (Coles et al. 1988; Gratton et al. 1990; Ghering et al. 1992). They concluded that the appearance of a hemispheric amplitude asymmetry of the RP in the 100 msec period prior to response is correlated with the choice of limb making the response.

We have examined in normals the relationship between the potentials that both precede and follow stimulus presentation to the motor response (RT). We utilized a target detection task requiring a RT or mental count response. We defined the presence of a slow negative potential shift before almost every stimulus in the target detection task. The relations of the pre-stimulus negativity to stimulus variables (target/non-target, stimulus sequence), to instructional variables (press or count), to behavioral variables (RT speed), and to the premovement negative shift accompanying self-paced movements are presented below.

Methods

Subjects

The subjects were 12 normal individuals (9 women, 3 men), ages 31–48 years (mean = 38.2 years), 10 of whom were right-handed and 2 left-handed. The subjects were studied in the morning. Individuals were recruited, signed informed consent forms and were tested following university guidelines for approved projects involving human subjects.

Target detection task

The subject was asked to detect each occurrence of an infrequent auditory "high" pitched target note (D, 1 octave above middle C) occurring infrequently ($P = 0.2$) among "low" pitched notes (middle C). The notes were synthesized by a computer and consisted of the fundamental and their harmonics. The auditory signals (250 msec duration, 60 dB nHL intensity) were presented by earphones every 2 sec. The "high" targets were randomly interposed between the frequent low pitched notes with the constraint that no 2 targets could occur in succession. The same stimulus sequence was used for all subjects. The task was presented twice on the test day with the order of presentation counterbalanced among subjects: (1) they were instructed to respond "without delay" as soon as they heard the high-frequency note with a rapid press on a response button using the thumb of their dominant hand; (2) subjects were to keep a mental count of the targets and the response button was not placed in the hand. The subjects were seated in a comfortable chair in a sound attenuating chamber and instructed to keep their eyes open and to look at a fixation spot straight ahead. They were instructed to refrain from blinking during the test period. The test sequence consisted of 300 stimuli comprised of 240 frequent low notes and 60 target high notes.

Self-paced movements

The subject was instructed to make a rapid opposition of the thumb towards the little finger at approximately 5–10 sec intervals. Sixty movements were recorded. Self-paced movements were recorded after the target detection tasks.

Brain and muscle (EMG) potential recordings

Disc electrodes were placed over Fz, Cz, Pz, C3′ and C4′ (1 cm anterior to C3 or C4) each referenced to linked electrodes at A1 and A2. Eye blinks were moni-

tored by electrodes situated above and at the lateral lower lid of the right eye. Muscle potentials (EMG) of the thenar muscles of the dominant hand were recorded between an electrode over the belly of the *opponens* muscle of the thumb and an electrode over the tendon at the metacarpophalangeal joint of the thumb. The brain potentials were amplified 200,000 times and the eye potentials were amplified 100,000 times and both were filtered (3 dB down) 0.01–100 Hz (time constant = 16 sec). Skin impedances measured below 3.0 kΩ. The muscle potentials were amplified 20,000 times and filtered (3 dB down) between 30 and 10,000 Hz.

Computer interface

For the target detection task, a microcomputer controlled the stimulus sequence and recorded reaction times. A second computer digitized the brain and muscle potentials. The digitized activities (256 points/channel) of the session were stored in computer memory and later saved to disk. The analysis epoch was 1.44 sec and included a pre-stimulus period of 0.76 sec duration. For self-paced movements the potentials were digitized (1024 points/channel) for 2.4 sec including a 1.6 sec period prior to EMG onset and were stored in computer memory and later saved to disk.

Averaged potentials

For the target detection task, averaged brain potentials were computed from the individual stored files. The type of stimulus (infrequent targets or frequent non-targets) and the latency of button press were included in each file. The digitized wave forms from each trial were displayed and examined on the computer screen. Trials were sorted by stimulus type (targets or non-targets) and averaged using 2 different triggers, stimulus onset or EMG onset. Error rates were approximately 1–2%. Only those trials with correct responses (button press for high notes or no button press for frequent low notes) were included in the averages. If the trial were compromised by potentials from eye blinks (up to 10% of the trials) a compensatory adjustment of the scalp distribution of potentials was made. An algorithm modified after Gratton et al. (1983) used the recorded eye channel as a template for subtraction of a scaled potential from each electrode site. The adjusted potentials were examined and, if the blinks

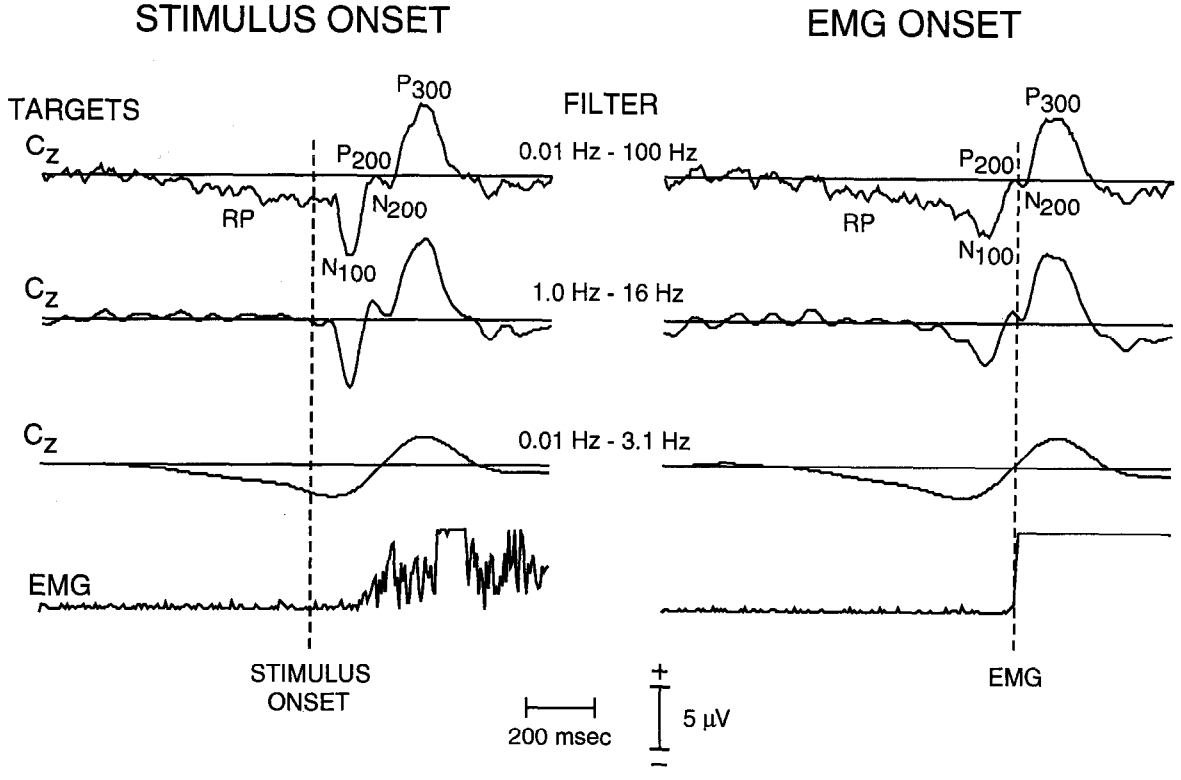

Fig. 1. Averaged potentials to targets recorded between Cz referenced to linked earlobes (first 3 traces) along with the rectified EMG (fourth trace) from 1 subject. The averages were computed using stimulus onset (left column) and EMG onset (right column). The components are identified by their polarity (P or N for positive or negative, respectively) and approximate latency in msec. RP is a slow negative shift preceding both stimulus and EMG onset. The raw averages in the top line (0.01–100 Hz) were bandpass filtered: first, from 1 to 16 Hz (traces in second line) to attenuate the slow RP for measurement of the amplitudes of the event-related peaks; second, from 0.01 to 3.1 Hz (traces in third line) to attenuate the event-related components for measurement of the amplitude of the RP. In this and all subsequent figures positivity at the "active" electrode (in this case Cz) is plotted up; a 5 μV calibration is provided for reference for evoked potentials; and a horizontal line is drawn through the average voltage in the baseline period.

were visually absent, the trial was included in the average. For self-paced movements the individual trials were displayed and aligned to the onset of the EMG response, and the trial included in the average after adjustment for any eye blink potentials.

A separate analysis of the single trials of both the target detection and the self-paced movement tasks was used to compute averages time-locked to the motor response. The EMG activity from the thenar muscle was full-wave rectified and a cursor aligned on the onset of the muscle potentials. All channels were then shifted automatically so that EMG onset for the target detection task was at the 1.00 sec point of the 1.44 sec sweep providing 1.00 sec of premovement and 0.44 sec of postmovement brain activity. For self-paced movements the alignment process provided for the averages to have a 1.6 sec period preceding EMG onset and a 0.8 sec period following EMG onset.

Averaged potentials in the target detection task

For each subject the following averaged potentials were computed. Stimulus triggered: to the targets; to the non-targets; to the targets as a function of the number of immediately preceding non-targets (target after 1 non-target, 2 non-targets, ... and n non-targets); to the non-targets as a function of their position relative to the target (immediately before or immediately after the target); to the non-targets as a function of their position in the sequence of non-targets following the target, e.g., the first non-target following the target (t + 1), the second non-target following the target (t + 2), etc.; and to the target as a function of RT speed separated into the fastest 1/3, the slowest 1/3, and the middle 1/3.

Response (EMG onset) triggered: to the targets as a function of the number of immediately preceding non-targets (target after 1 non-target, 2 non-targets, ... and n non-targets); and to the target as a function of RT speed separated into the fastest 1/3, the slowest 1/3, and the middle 1/3.

Data analysis

The averaged potentials were bandpass filtered using FFT and inverse FFT procedures. For measuring

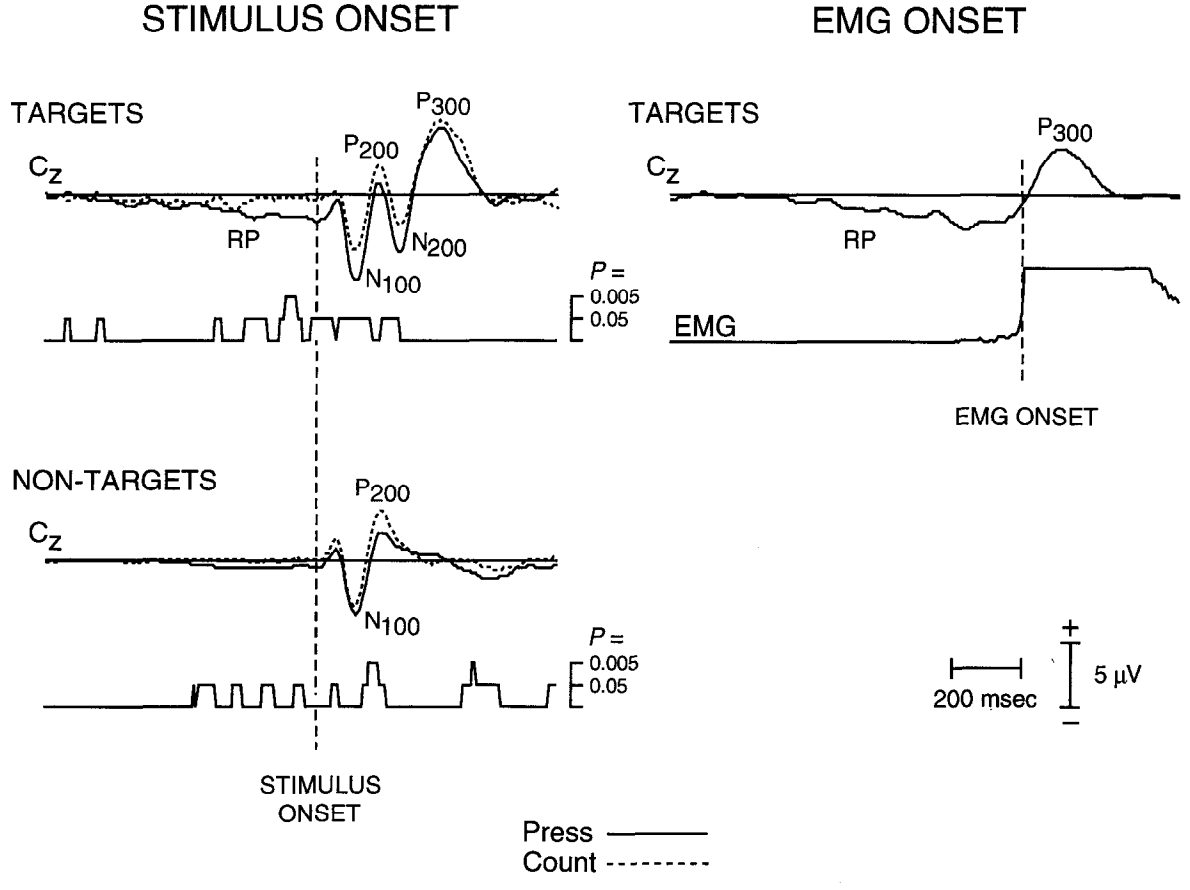

Fig. 2. Grand averaged potentials (Cz to linked earlobes) using stimulus onset (traces in left column) and EMG onset (traces in right column) to targets and non-targets as a function of instruction (Press, solid line; Count, interrupted line). Differences (*t* tests) in the amplitude (press vs. count instruction) of the averages to stimulus onset are indicated. The negative potential shift (labeled RP) is larger in the press than count conditions for a 400 msec period straddling stimulus onset. In the averaged potential to EMG onset to targets in the press condition, a RP and P300 potentials are evident but the N100, P200 and N200 components are attenuated.

amplitudes and latencies of the various components and slow potential shifts in the target detection task, the averaged potentials were filtered in 2 ways (Fig. 1). First, to define the peak latencies and amplitudes of sensory and cognitive components (N100, P200, N200, P300) in the absence of the slow potential shifts, the bandpass filter was set from 1 to 16 Hz. The peak amplitudes were defined relative to the average amplitude in a 751.25 msec period prior to the stimulus. The peak latency was defined from the largest excursion of the component. The identification of N200 and P300 components to non-target stimuli was often difficult because of their low amplitudes relative to the baseline fluctuations. The criteria were that N200 was the initial negative going peak after P200 and P300 was the initial positive going peak after P200. The termination of the P200/300 component to non-targets was when the negative going limb of this component leveled off. Second, for measuring the amplitudes of the sustained pre-stimulus and premovement potentials in the absence of sensory components in the target detection task as well as during self-paced movements, the wave forms were low-pass filtered (zero-phase-shift digital filter, 0.01–3.1 Hz, 12 dB down). Averaged amplitude measures in a 300 msec window preceding stimulus onset and in a 500 msec window preceding EMG onset were computed relative to the average amplitude in a 120 msec period at the beginning of the averaged epoch. The window lengths were based on the grand averages to encompass the major portions of the negative potential shifts. The onset latency of the slow potential shift relative to stimulus and to EMG onset was also defined.

Statistical analysis

Measures of latency, amplitude (peak for N100, P200, N200, P300 and averaged amplitude in a window of time for the pre-stimulus negative potential), and RT (the latency of the button press response) were tested for significance by analysis of variance (ANOVA) procedures for repeated measures with the Greenhouse-Geisser correction. Factors examined included instruction (press vs. count) and stimulus type (target vs. non-target) on event-related potentials at Pz and pre-stimulus negative shift at Cz; stimulus sequence (number of immediately preceding non-targets; 1–2, 3–4, > 4) and instruction (press vs. count) on potentials accompanying targets; instruction (press vs. count) and stimulus sequence on potentials accompanying non-targets as a function of their position in the stimulus sequence following the targets (the first, the second, the third, the fourth, and greater than the fourth);

TABLE I

Target and non-target averaged potentials. Component peak latency (msec) and peak or averaged amplitude (μV) as a function of response instruction ("Press" response button; keep mental "Count") and the event (stimulus or EMG response) used to compute the averages (mean values at Pz except RP defined at Cz, here and subsequent tables).

	Stimulus onset				EMG onset	
	Targets		Non-targets		Targets	
	Latency	Amplitude	Latency	Amplitude	Latency	Amplitude
N100						
Press	109	−2.84	104	−2.98		
Count	105	−2.55	103	−2.93		
P200 [a]						
Press	176	3.87	198	3.00		
Count	174	3.29	188	3.22		
N200 [b]						
Press	233	−0.67	265	0.40	−48 [†]	−0.13
Count	227	−0.60	245	1.28		
P300 [c]						
Press	350	9.20	324	1.42	93 [†]	9.47
Count	354	8.27	293	1.91		
RP [d]	(300 msec window)				(500 msec window)	
Press	−441	−1.36	−315	−0.47	−722	−1.51
Count	−308	−0.35	−140	0.08		
Press C_{contra}/C_{ipsi}	−1.02/−0.99				−1.38/−1.14	

RP = readiness potential; C_{contra} and C_{ipsi} refer to the central recording sites, C3′ or C4′, corrected for the hemisphere contralateral or ipsilateral to the responding hand. Average amplitude was computed over a specified time domain (i.e., 300 msec, 500 msec).

[†] Latency relative to EMG onset: a minus sign indicates the component occurs before EMG onset. For averages to stimulus onset:

[a] P200 latency ($P = 0.006$) for stimulus type (Targets vs. Non-targets).

[b] N200 latency ($P = 0.006$) and amplitude ($P = 0.01$) for stimulus type (Target vs. Non-targets).

[c] P300 latency ($P < 0.001$) and amplitude ($P < 0.001$) for stimulus type (Target vs. Non-targets).

[d] RP amplitude ($P < 0.001$) for stimulus type (Target vs. Non-targets); amplitude ($P < 0.001$) for instruction (Press vs. Count).

speed of response (RTs divided into fastest third, slowest third, and middle third) on potentials accompanying targets in the press condition; scalp recording site (midline sagittal position, Fz, Cz, Pz, and lateral position, C3′ vs. C4′) on the premovement negative shift in a 500 msec window during self-paced movements and during the press condition of target detection. Differences at $P < 0.05$, or better were considered significant. Post-hoc differences among the means were tested using Fisher's LSD (P level set at 0.05). Correlation and regression procedures were used to evaluate the relationships between amplitude and latency of pre-stimulus negative potentials, RT, and event-related potentials, and between the amplitude and latency of the premovement negativity during self-paced and target detection tasks.

Results

"Press" vs. "count" instruction

Stimulus and response (EMG onset) triggered grand averages for targets and non-targets are contained in Fig. 2. A pre-stimulus negative shift was evident in the button press but not the mental count condition to both rare target and frequent non-target stimuli. The averaged amplitude of the negative shift at Cz preceding stimulus onset was significantly ($P = 0.001$) larger for the press than the count instruction and larger for targets (-1.36 μV vs. -0.35 μV for targets, respectively) than non-targets (-0.47 μV and 0.08 μV for non-targets) (Fig. 2, Table I). The pre-stimulus negative shift to targets in the count condition (-0.35 μV) was not significantly different from baseline levels ($P = 0.06$).

The negative shift began approximately 400 msec before stimulus onset and continued for several hundred msec after stimulus onset displacing the N100, P200 and N200 components in a negative direction. The onset latency of the negative shift to both targets and non-targets was earlier with the press than the count instruction (-440 msec vs. -308 msec for targets, and -315 msec vs. -140 msec for non-targets, respectively) but the differences did not achieve significance ($P = 0.07$). We have labeled this negative potential a readiness potential (RP) since it appeared prior to stimulus onset when the instructions were to make a motor response to target stimuli. Peak latencies and amplitudes of sensory (N100, P200) and cognitive (N200, P300) components to rare target and frequent non-target notes in the stimulus triggered averages (measured after filtering out the slow potential shift) were not different as a function of instruction (button press or mental count, Table I). In the EMG response triggered averages to target stimuli, the sensory components (N100, P200) were markedly attenuated whereas the N200 and P300 components could be still defined. N200 peaked approximately 50 msec before EMG onset and P300 peaked approximately 100 msec after

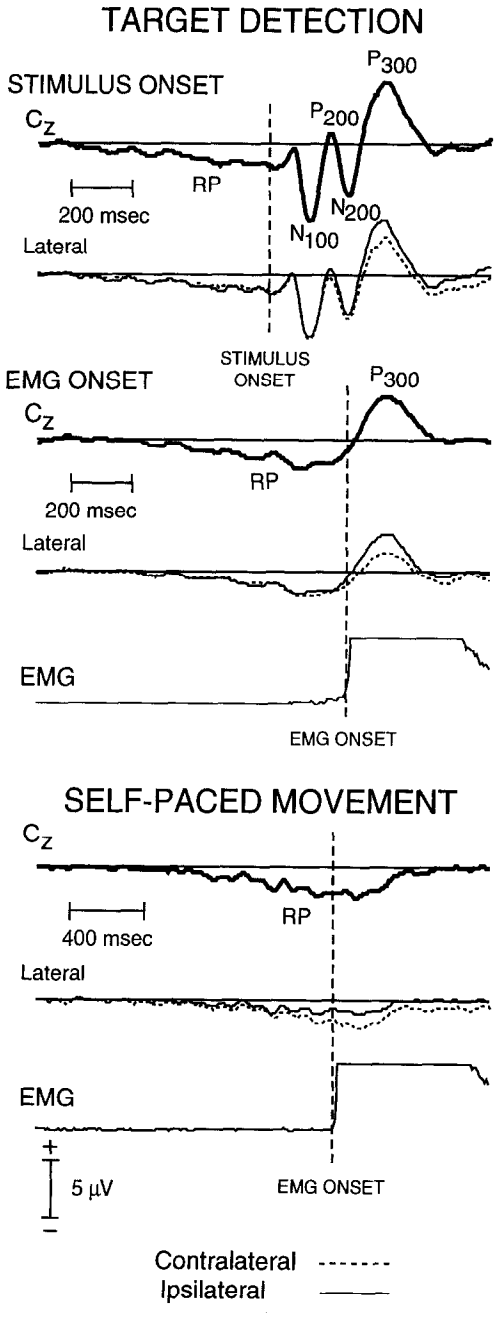

Fig. 3. Grand averaged potentials from Cz (bold trace) and from lateral recording sites (traces just below Cz) adjusted so that when "contralateral" to the responding hand making a motor response, the trace is interrupted and when "ipsilateral" to that hand the trace is not interrupted. The averages in the target detection task were computed for stimulus and EMG onsets. The amplitude of the RP was symmetrical over the hemispheres prior to both stimulus and EMG onsets. In contrast, the amplitude of the RP for self-paced movements (bottom of figure) was asymmetrical (contralateral > ipsilateral) during the approximately 200 msec period both prior to and following EMG onset. Note that the time calibrations for target detection and self-paced movements differ.

EMG onset. The negative RP began approximately 700 msec before EMG onset and returned to baseline during the P300 component.

Stimulus type (targets vs. non-targets)

Post-stimulus components.. The potentials differed as a function of stimulus type independent of instruction (see Table I for means of amplitudes and latencies, see Fig. 2 for grand averages). N200 peak amplitude (filtered to remove the slow potential shift) was significantly more negative ($P = 0.01$) and of shorter latency ($P = 0.006$) for targets than for non-targets. P300 amplitude was significantly ($P < 0.001$) larger for targets than non-targets and significantly lateralized to the ipsilateral hemisphere (C4′ > C3′, $P = 0.001$; Fig. 3). P300 latency was longer for the targets than for the non-targets. The P200 latency difference between targets and non-targets was significant ($P = 0.006$).

Pre-stimulus components.. A negative potential (designated as RP) preceded targets in the press condition in 9 of the 12 subjects in the stimulus triggered averaged potentials (Fig. 3); one of the subjects without a negative shift in the stimulus triggered average did show a negative shift when the averages were computed from EMG onset. The correlation between amplitude (window) measures of the negative potential using stimulus-locked onsets (300 msec window) and EMG onsets (500 msec window) was significant ($r = 0.83$; $P < 0.001$). The scalp distribution of the negative shift in the averages to EMG onset was significantly ($P = 0.01$) larger at Cz (-1.51 μV) than at either Fz (-1.13 μV) or Pz (-0.79 μV) but differences between the hemispheres did not achieve statistical significance (contralateral = -1.38 μV, ipsilateral = 1.14 μV; Table I, Fig. 3).

Self-paced movements

When the subjects made a regular voluntary self-paced thumb flexion, a premovement negativity (RP) was recorded (Fig. 3) that was significantly larger at Cz than either Pz or Fz (average amplitude (μV) at Fz = -1.73; Cz = -2.06; Pz = -0.61; 500 msec window

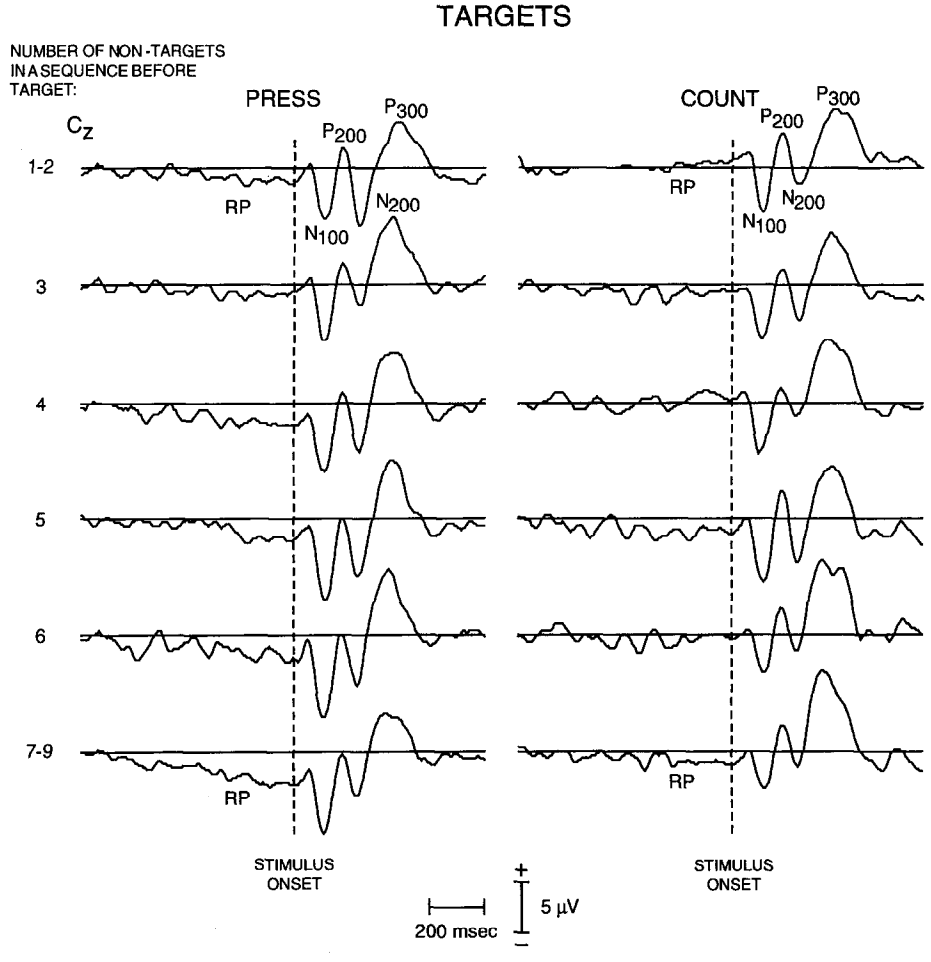

Fig. 4. Grand-averaged potentials to targets selected according to the number of immediately preceding non-targets (1–2, 3, 4, ..., n) for the press and count conditions. Note that the amplitude and onset latency of the RP increases with the number of immediately preceding non-targets in the press condition. In contrast, the RP is either of small amplitude or not present in the count condition. See Table II for measures of these potentials.

TABLE II

Target potentials averaged to stimulus onset. Component peak latency (msec), peak or averaged amplitude (μV) and reaction times (RT) as a function of the number of immediately preceding non-targets, e.g., target preceded by 3 and 4 non-targets is "3–4" (mean values).

	Latency			Amplitude		
No. of preceding non-targets:	1–2	3–4	> 4	1–2	3–4	> 4
N100						
Press	111	105	111	−3.41	−3.27	−4.18
Count	114	100	111	−2.88	−3.08	−2.70
P200						
Press	178	173	172	4.44	3.52	3.30
Count	177	168	179	4.54	2.86	4.24
N200 [a]						
Press	242	228	215	−2.90	−0.50	−1.30
Count	235	215	226	−1.31	−0.77	−1.33
P300 [b]						
Press	385	341	336	8.85	10.32	10.38
Count	363	341	336	8.45	8.52	9.98
RP [c]				(300 msec window)		
Press	−263	−506	−542	−1.16	−1.30	−2.41
Count	−165	−210	−356	0.33	−0.50	−0.75
RT [d]						
Press	388	344	333			

[a] N200 latency ($P = 0.005$) for stimulus sequence; for Press > 4 earlier than 3–4, earlier than 1–2; for Count > 4 and 3–4 earlier than 1–2.
[b] P300 latency ($P < 0.003$) for stimulus sequence; for both Press and Count > 4 and 3–4 earlier than 1–2.
[c] RP latency ($P = 0.03$) for instruction (Press vs. Count) and stimulus sequence ($P = 0.01$); for Press > 4 and 3–4 earlier than 1–2; for Count, > 4 earlier than 1–2. RP amplitude for instruction ($P = 0.05$) and stimulus sequence ($P = 0.001$); for Press > 4 more negative than 3–4 and 1–2; for Count, > 4 more negative than 1–2 and 3–4.
[d] RT difference for stimulus sequence ($P < 0.001$); RTs for > 4 and 3–4 were faster than for 1–2.

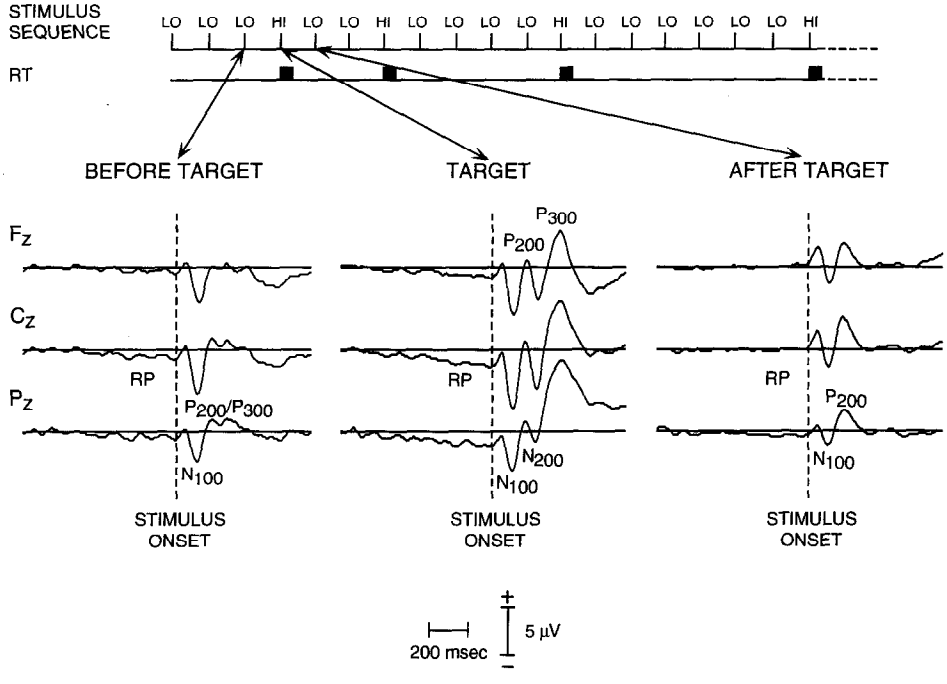

Fig. 5. Grand-averaged potentials to stimulus onset for targets and non-targets just before and just after the targets. The arrows show how the stimuli were segregated into separate averages for the sequence around 1 target. This process was repeated for all targets. Note the RP to targets and to non-targets just before the target but its absence to the non-targets just after the targets. A P300 component (labeled P200/300) is evident to non-targets preceding but not following the targets. Note that the N100 was significantly reduced at Cz ($P < 0.01$) in amplitude after the target compared to both the N100 to the target and the N100 immediately before the target.

preceding EMG onset). The premovement negativity accompanying self-paced movements was significantly ($P = 0.01$) larger over the hemisphere contralateral (-1.61 μV) than ipsilateral (-1.20 μV) to the responding thumb (Fig. 3). The correlation of the averaged amplitudes of the negative potential shifts preceding self-paced thumb movements and those preceding thumb movements in target detection were not statistically significant.

Stimulus sequence

Rare targets.. The stimulus sequence affected the evoked potentials to targets. Fig. 4 contains the grand average from all subjects of the potentials to targets when preceded by 1–2, 3, 4, 5, 6 or > 7 non-targets. The amplitude of the RP and the latencies of some of the components appear to change as a function of the stimulus sequence. To quantify these changes, the targets were separated into 3 categories and reaveraged (targets preceded by 1–2 non-targets (17 possible trials), targets preceded by 3–4 non-targets (22 possible trials) and targets preceded by > 4 non-targets (21 possible trials)). Significant changes were defined (see Table II) for the latency of N200 ($P = 0.005$) and P300 ($P < 0.003$) independent of instruction (press and count conditions). Post-hoc comparisons showed that N200 and P300 latencies were earlier for targets preceded by > 4 non-targets than for targets preceded by 3–4, and/or 1–2 non-targets. An interaction between stimulus sequence and instruction of marginal significance ($P = 0.06$) was found for N200 latency. The onset of the RP ($P = 0.01$) and its amplitude ($P = 0.001$) were significantly affected by stimulus sequence with post-hoc tests showing RP latency to be earlier and its amplitude higher to targets preceded by 3–4 and/or by more than 4 non-targets than to targets preceded by 1–2 non-targets. RPs were also significantly affected by instruction being larger ($P = 0.05$) and earlier ($P = 0.03$) in the press than the count condition. However, the amplitude of the RP in the count condition was significantly different from baseline for targets preceded by > 4 non-targets ($P = 0.008$) and was of marginal significance for targets preceded by 3–4 non-targets ($P = 0.06$). All 12 subjects had a negative RP in the press condition to targets when preceded by a string of > 4 non-targets. Reaction times were significantly longer ($P < 0.001$) to targets preceded by only 1–2 non-targets compared to targets preceded by 3–4 and more than 4 non-targets. Regression procedures were applied to examine the relationship between component measures and RT. Significant correlations were

TABLE III

Non-target potentials averaged to stimulus onset. Component peak latency (msec) and peak or averaged amplitude (μV) as a function of instruction (button press or mental count of targets) and position of non-targets in stimulus sequence following the target, e.g., first stimulus after target (t+1), second (t+2), etc. (mean values).

	Latency					Amplitude				
Position in sequence:	t+1	t+2	t+3	t+4	t>4	t+1	t+2	t+3	t+4	t>4
N100										
Press	102	109	111	106	108	−2.17	−2.89	−3.21	−3.49	−3.72
Count	103	106	111	110	106	−3.34	−2.63	−3.44	−3.40	−3.17
P200										
Press	180	194	197	197	197	3.03	2.38	3.39	2.99	3.06
Count	175	182	188	186	188	2.49	1.63	1.85	2.16	1.51
N200										
Press	244	261	247	259	243	0.66	−0.15	−1.39	0.93	1.11
Count	243	242	250	232	232	1.02	0.37	0.24	−0.01	0.68
P300 [a]										
Press	286	330	298	316	323	1.88	1.10	1.94	2.69	2.99
Count	301	283	298	295	298	1.86	1.50	1.79	2.96	2.86
P200/300end [b]										
Press	374	417	412	431	457					
Count	361	339	362	394	382					
RP [c]						(300 msec window)				
Press	−242	−216	−345	−390	−476	0.19	−0.03	−1.47	−2.00	−2.38
Count	−121	−87	−381	−367	−290	0.41	0.63	−0.91	−0.56	−0.56

[a] P300 latency ($P = 0.02$) for instruction and ($P = 0.04$) for instruction × stimulus sequence. P300 amplitude ($P = 0.01$) for stimulus sequence; for Press, t > 4 and t+4 larger than t+2; for Count, t > 4 and t+4 larger than t+1, t+2, and t+3.

[b] P200/300end latency ($P < 0.001$) for instruction and stimulus sequence ($P = 0.04$); for Press, t > 4 and t+4 longer than t+1; for Count, t > 4 and t+4 longer than t+2.

[c] RP latency ($P = 0.007$) for stimulus sequence; for Press, t > 4 earlier than t+1 and t+2; for Count, t > 4, t+4 and t+3 earlier than t+2. RP amplitude ($P = 0.05$) for instruction and for stimulus sequence ($P = 0.003$); for Press, t > 4, t+4 and t+3 more negative than t+1 and t+2; t+3 more negative than t+1; for Count, t > 4, t+4 and t+3 more negative than t+2; t+3 more negative than t+1 and t+2.

defined for N100 amplitude ($r = 0.37$; $P = 0.02$) and N200 latency ($r = 0.71$; $P < 0.001$).

Frequent non-target stimuli.. The potentials to non-targets were also affected by stimulus sequence (Fig. 5). A pre-stimulus negative shift (RP) was present to non-targets immediately preceding targets but was absent to non-targets immediately following targets. The P200 component to non-targets immediately preceding targets was prolonged (the component is labeled P200/300 in Fig. 5) compared to the P200 to non-targets immediately following the targets.

The potentials to non-targets were then analyzed according to their relative position in the stimulus sequence following the targets, i.e., non-target just after the target (target + 1), non-targets that were the second non-target stimulus after the target (t + 2) etc. (Table III, Fig. 6). The N100 and P200 components were unaffected by stimulus sequence or instruction. The positivity accompanying the P200 broadened as the number of non-targets following the target increased (see Fig. 6) with the peak latency of the late positivity approaching that of the P300 accompanying rare target stimuli (323 msec vs. 350 msec). P300 latency was significantly longer ($P = 0.02$) with the press than the count instruction and was affected by stimulus sequence but only to the press condition (instruction × stimulus sequence interaction, $P = 0.04$), while P300 amplitude ($P = 0.01$) was affected by stimulus sequence independent of instruction. The duration of the P200/300 component and RP amplitude and latency were significantly affected by both instruction and by stimulus sequence (Table III, Fig. 7). Post-hoc tests showed the duration of the P200/300 component to be significantly longer for non-targets late in the stimulus sequence (t + 4, t > 4) compared to early positions (t + 1 or t + 2). The RP was of smaller amplitude for non-targets immediately following the rare target tones (t + 1 and t + 2), compared to subsequent non-targets in the sequence (t + 3, t + 4, t > 4). The difference in RP amplitudes between targets and non-targets defined in the grand averages (Fig. 2, Table I) does not hold up when stimulus sequence is also considered. Thus, the RP is of similar amplitude to targets and

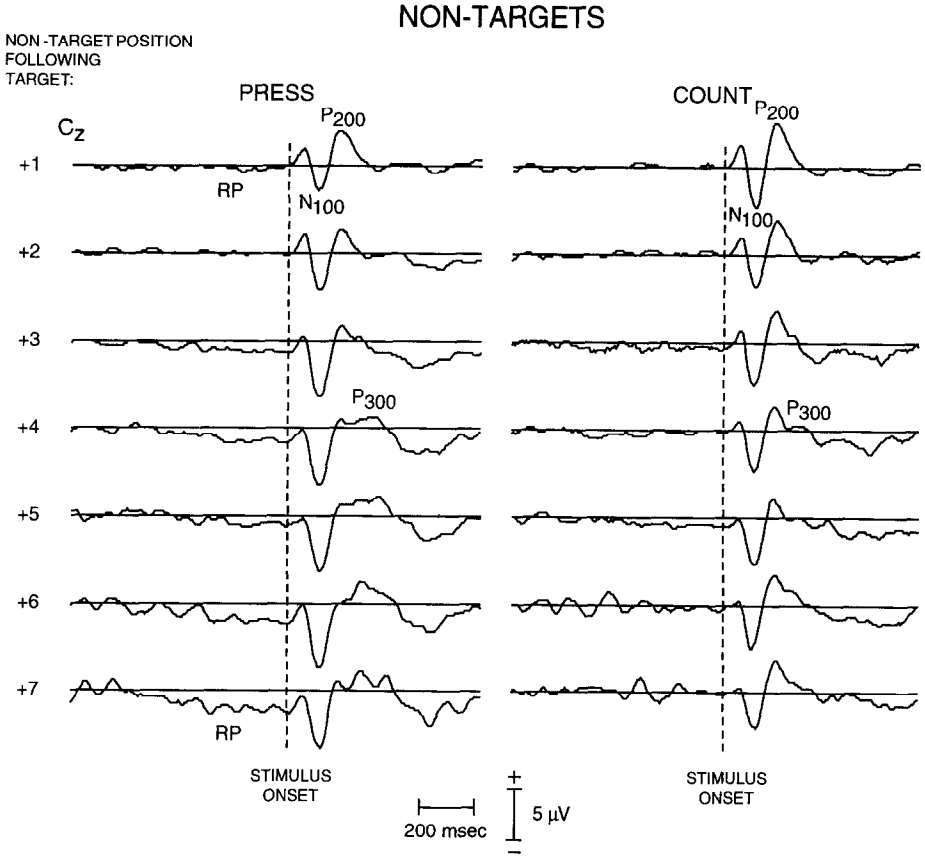

Fig. 6. Grand-averaged potentials to non-targets sorted according to their position in the stimulus sequence following the targets (+1, +2, +3, ..., +n) for the press and count conditions. In the press condition, both the amplitude and onset latency of the RP increased as the number of non-targets occurring in sequence advanced. In contrast, the RP is either of small amplitude or not present in the count condition. As the number of non-targets in sequence increases, the P200 component is prolonged in duration into the time of the P300 component (labeled P300) and is then followed by a negative component. This is particularly prominent in the press compared to the count condition. See Fig. 7 for a graph of these results and Table III for the measures of the potentials.

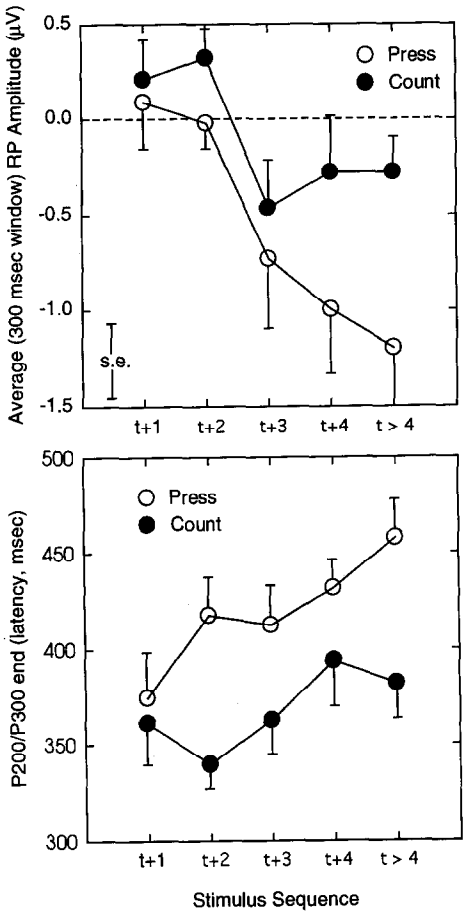

Fig. 7. The relation of RP amplitude (top graph) and the end of the P200/300 component to non-targets (bottom graph) as a function of position in the stimulus sequence (i.e., the first non-target following a target is t+1, the second non-target in sequence is t+2, etc.). The measures are for the press and count conditions. Note the increase in amplitude of the RP and the lengthening of the P200/300 component in the press condition as the position of the non-target in sequence advances.

non-targets (−2.38 μV vs. −2.40 μV, respectively) when equated for equal numbers of immediately preceding non-targets (e.g., > 4 non-targets, see Tables II and III, and Figs. 4 and 6).

The relation of brain potential measures to reaction times.. For each individual the target trials were separated into 3 equivalent groups comprising 3 levels of RT speed: the fastest 1/3 (averaging 286 msec), the slowest 1/3 (averaging 417 msec) and the middle 1/3 (averaging 343 msec). Stimulus and response triggered averages to targets divided for the RT speed are in Fig. 8 and the measures of component amplitudes and latencies are in Table IV. In the stimulus locked averages, both the N200 and P300 components decreased significantly in latency ($P < 0.001$ and $P < 0.001$) and increased in amplitude ($P = 0.01$ and $P = 0.009$), respectively, with RT speed. Both RP latency and amplitude increased with RT speed but the changes were of marginal significance ($P = 0.05$ and $P = 0.08$, respectively). There were no significant effects for the N100 and P200 components as a function of RT groups. Regression procedures were applied to examine the relationship between component latencies and RT, and component amplitudes and RT. Significant correlations were found for N200 latency ($r = 0.68$; $P < 0.001$), P300 amplitude ($r = -0.47$; $P = 0.003$) and latency ($r = 0.45$; $P = 0.004$), and RP amplitude ($r = 0.45$; $P = 0.005$). In the response locked averages (right side of Fig. 8) the N100 and P200 components are markedly attenuated, the N200 is present but of reduced amplitude, whereas the P300 is of an amplitude comparable to that seen in the stimulus locked averages. The relative timing of N200 and P300 and EMG onset changed with RT speed. The peak of N200, which also

TABLE IV

Target averaged potentials. Component peak latency (msec) and peak or averaged amplitude (μV) as a function of reaction times (RT). The trials for each subject were separated into the fastest 1/3, the slowest 1/3, and the medium 1/3.

	Latency			Amplitude		
	Fast	Medium	Slow	Fast	Medium	Slow
Trigger						
Stimulus						
N100	107	109	111	−3.14	−1.88	−3.25
P200	170	178	179	4.47	3.72	4.39
N200 [a]	215	231	242	0.16	−1.07	−3.31
P300 [b]	328	342	359	10.02	9.69	7.94
RP [c]						
Trigger						
Stimulus	−565	−466	−356	−1.82	−1.47	−0.77
EMG	−637	−518	−625	−1.80	−1.11	−0.93
RT [d]	286	343	417			

[a] N200 latency ($P < 0.001$); Fast < Medium < Slow. N200 amplitude ($P = 0.01$); Fast less negative than Medium, less negative than Slow.
[b] P300 latency ($P < 0.001$); Fast < Medium < Slow. P300 amplitude ($P = 0.009$); Fast and Medium > Slow.
[c] RP (stimulus onset) latency ($P = 0.05$); Fast > Medium > Slow. RP amplitude (marginal, $P = 0.08$); Fast > Slow.
[d] RT ($P < 0.001$); Fast < Medium < Slow.

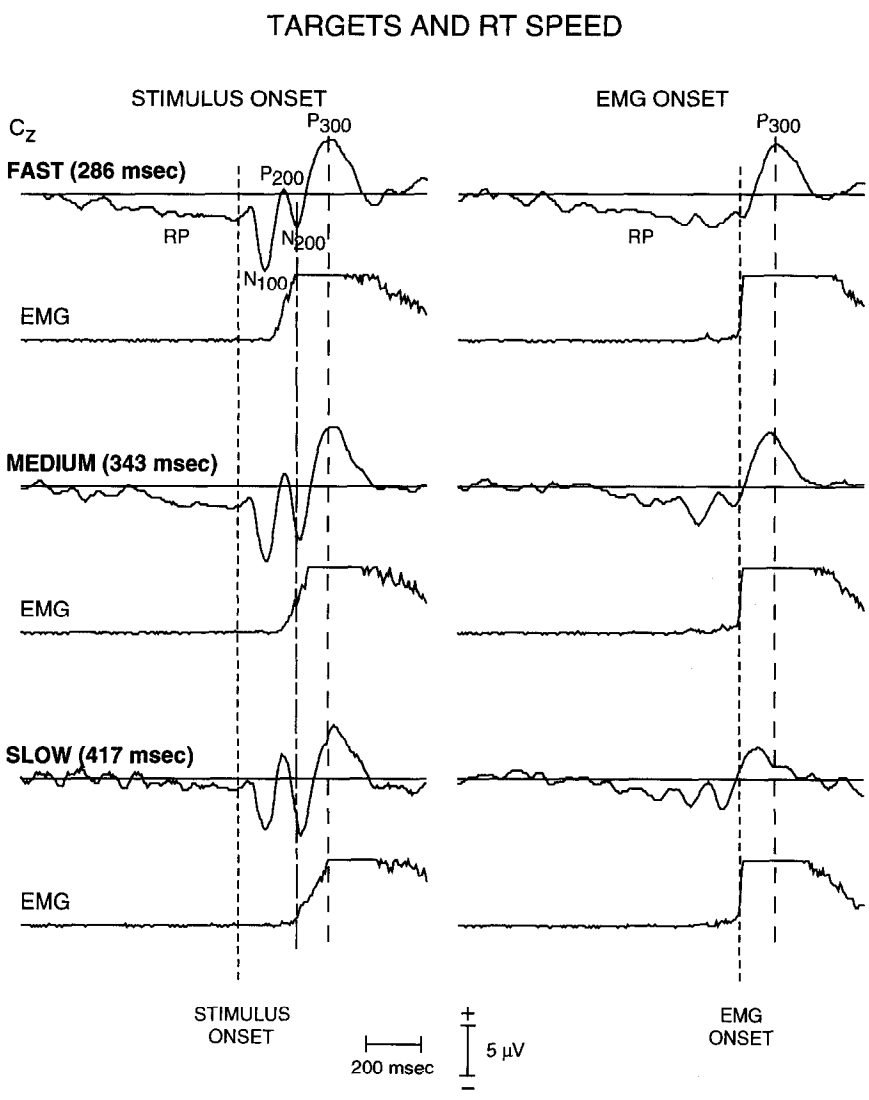

Fig. 8. Grand-averaged potentials and the EMG (rectified) to targets subdivided by reaction time (RT) speeds. The single trials for each subject were reaveraged according to RT speed into "fast" (fastest 1/3 of the trials), "medium" (middle 1/3), and "slow" (slowest 1/3). The averages were calculated for both stimulus and EMG onsets. The RP is large for the fast and medium RT trials compared to the RP to trials comprising the slowest 1/3 RT. In the stimulus triggered averages, both the N200 and P300 are of shorter latency to the fast than to the slow RT trials. In the stimulus onset triggered averages, the latency of N200 and P300 are earlier with fast than slow RTs (see alignment lines). In the EMG onset triggered averages, the onset of the P300 component relative to EMG onset changes from being almost simultaneous with the fast RT averages to that of preceding EMG onset by approximately 100 msec in the slow RT averages.

marked the onset of P300, is almost coincident with EMG onset on those trials with fast RTs, and shifts to precede EMG onset on those trials with slow RTs. These results support the concept that processes regulating the timing of N200 and P300 and those regulating the timing of RT are closely related.

Discussion

This study revealed a slow negative potential shift to precede both targets and non-targets in the target detection task. The negative potential's amplitude and onset latency were affected by the type of response (button press vs. mental count of the targets) and by the immediately preceding stimulus sequence. We have classified the negative potential shift as a type of readiness potential (RP) because its amplitude significantly increased with instructions requiring motor preparation ("press the button when the target appears") compared to mental preparation ("make a mental count when the target appears"). Barrett et al. (1987) deduced that a RP was probably present in the target detection task since the N200 and P300 components were more negative at Cz and C3 during button press (the subjects used their right hands for the response) than during mental counting. The N200 and P300 in the present study were similarly displaced in a

negative direction over the central recording site contralateral to the responding hand (see Fig. 3). The detection of a pre-stimulus slow negative shift preceding stimulus presentation was facilitated in the present study by the use of long time constants and relatively long pre-stimulus analysis periods. Also, the rate of stimulus presentation was slowed to 1 every 2 sec to distinguish the pre- and post-stimulus related components.

The classification of slow negative shifts preceding movements or a stimulus signalling that a movement is to be made includes (1) readiness potential (Deecke et al. 1969), (2) contingent negative variation (Walter et al. 1964) and (3) stimulus preceding negativity or SPN (Brunia and Damen 1988). The slow negative shift preceding stimulus onset in our experiments did not have a right hemisphere predominance as has been reported with the SPN. It was largest over the central region (Cz) as has been reported with both the RP (Deecke et. al. 1969) and CNV (McCallum 1988). The pre-stimulus negative potential was not significantly lateralized to the hemisphere contralateral to the responding hand distinguishing it from the RP accompanying self-paced movements, and it was distinguished from a CNV by its attenuation when subjects kept a mental count of the targets, a condition which should not affect expectancy and CNV amplitudes (McCallum 1988). Thus, the pre-stimulus negativity does not slip easily into a CNV or a RP classification scheme. Our methods of analysis for slow potential shifts were limited to a 1.44 sec epoch surrounding each stimulus and led to the definition of a pre-stimulus negative potential relative to a baseline at the beginning of this time period. We recognize that the negative shift may be part of a long lasting slow potential shift extending over many stimuli as previously described in the target detection task (Deecke and Lang 1988).

The appearance of a low amplitude pre-stimulus negative shift during mental counting, a task that does not require movements, is a strong argument against its designation as a RP. However, mental counting can be accompanied by subtle activation of muscles of face, tongue and larynx (Hardyck and Petrinovich 1970). The possibility that neural events preceding such slight and unapparent movements could lead to the generation of the small pre-stimulus negative potential shifts during mental counting was examined in 2 subjects. We recorded potentials during the target detection task when the instructions were (1) "to make a mental count of the targets," (2) "to count the targets aloud" and (3) "to press the response button at each target." The cognitive act of counting is the same in the former 2 recording periods except that only counting aloud is associated with overt movements of lips, tongue, and

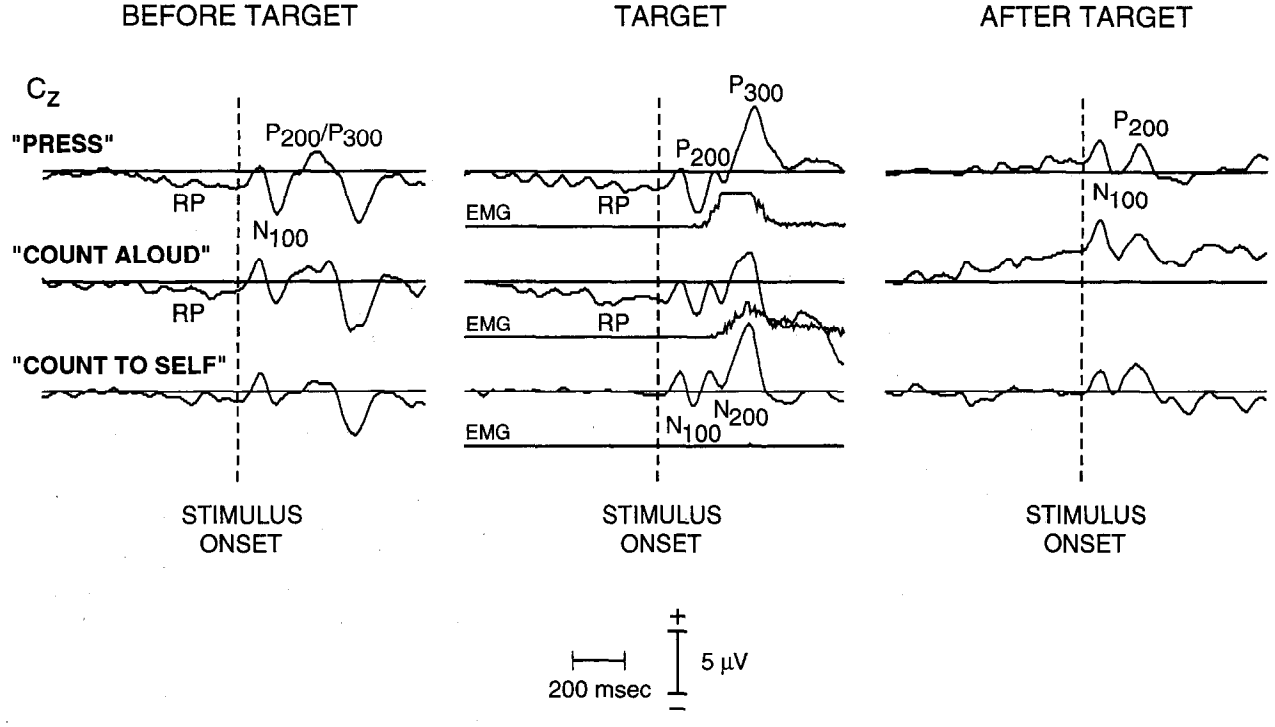

Fig. 9. Averages from a single subject to targets and to non-targets immediately preceding ("before target") and immediately following ("after target") targets. There were 3 conditions tested: (1) "press" the response button to each target; (2) "count aloud" each target; and (3) "count to self" each target. Recordings from Cz are shown along with the rectified EMG from the thenar muscle of the dominant hand in the press condition and from the perioral muscles in the count in your head and count aloud conditions. The RPs to targets and to non-targets immediately before targets are attenuated or absent in the count to self condition compared to count aloud or press conditions.

pharyngeal muscles. Results were similar in the 2 subjects and the averaged potentials from one of the subjects is shown in Fig. 9. A negative potential of large and similar amplitude appeared before both targets and the immediately preceding non-targets in the "button press" and "counting aloud" conditions but was absent or attenuated in the "mental count" condition. There were no negative potentials preceding non-targets immediately following the targets in all 3 conditions. Thus a motor response (button press or counting aloud) is critical for the appearance of a high amplitude pre-stimulus negative potential.

These same subjects were also tested in a CNV paradigm (low tone (S1) followed in 1.5 sec by a high tone (S2)) when the instructions were either "to count aloud" or "to keep a mental count" of the occurrences of high tones (S2). The CNV potential was essentially of the same amplitude in both the count aloud and mental count instructions (Fig. 10).

All of these observations indicate that the preparation to make a motor response to targets (button press or counting aloud) is critical for the development of large amplitude negative potentials preceding stimulus presentation in the target detection task. The persistence of a small pre-stimulus negativity when a motor response was not required (mental counting) could be due to 3 possibilities. First, mental counting may involve motor preparations even though no movements or EMG evidence of muscle activity are apparent and thus generate a RP. The recent studies of blood flow using positron emission tomography would lend support to such a hypothesis by the demonstration of left premotor and prefrontal cortical activity in humans during the silent generation of words (Wise et al. 1991). Second, mental counting may be accompanied by unapparent muscle activity and an accompanying RP. The failure to detect perioral muscle activity during mental counting in the 2 subjects tested does not exclude this possibility since other muscles involved in speech production, which were not monitored, may have been active. Third, the pre-stimulus negativity may be a CNV potential generated during the target detection task. The sequence of stimuli in the target detection task has attributes analogous to the stimulus sequence used to elicit a CNV (e.g., a warned RT). Each non-target serves as a warning signal (S1) that the next stimulus (S2) may require a response if it were a target. While our results do not eliminate any of these possibilities, we can conclude that the major portion of the pre-stimulus negative shift most likely represents a RP accompanying preparations to make a motor response.

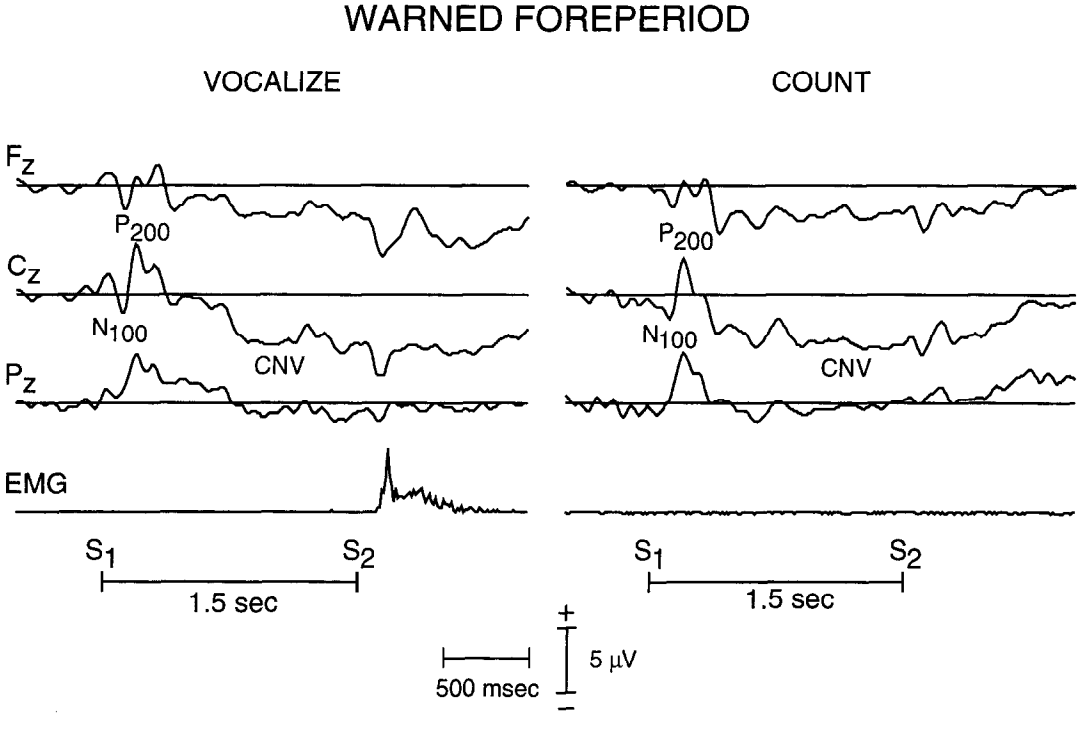

Fig. 10. Averaged potentials from the subject of Fig. 9 during a forewarned reaction time study (S1, a low tone precedes by 1.5 sec a high tone, S2). The task was carried out when the subject noted the occurrence of S2 by vocalizing "beep" or by mentally counting the occurrence of the high tone. A slow negative potential, labeled CNV, develops after S1 in both conditions. Averages are from 24 trials recorded from Fz, Cz, and Pz (T.C. = 16 sec) and the EMG (rectified) is from the perioral muscles. The total analysis epoch is 3 sec. Averages were low-pass filtered at 7.5 Hz, 6 dB down.

The absence of a significant hemispheric lateralization of the pre-stimulus negativity during motor response preparation is evidence that the generation of a RP in the relatively automatic response required in the target detection task (go, no-go) differs from the generation of the RP in self-paced voluntary movements. Kutas and Donchin (1980) demonstrated that the timing and scalp distribution of premovement negative potentials can vary with the requirements of the task (accuracy vs. speed of response) and the type of task (choice vs. simple RT). Coles et al. (1988) and Goodin et al. (1993) have shown that hemispheric lateralization of a premovement potential occurs in a 2-alternative forced-choice task in which the response entails the selection of which hand is to be moved.

Both RT (Remington 1969) and the N200 and P300 components of event-related potentials (Squires et al. 1976; Johnson and Donchin, 1982) can be affected by the immediately preceding stimulus sequence. In a now classical study, Squires et al. (1976) showed that the amplitude of the N200, P300 and a following slow wave were all larger as the number of non-targets preceding the target increased in number. The authors were not convinced of any accompanying P300 latency change. However, Barrett et al. (1986) defined that the latency of P300 in a somatosensory target detection task was affected by stimulus sequence. Hermanutz et al. (1981) described the presence of large P300 components to non-targets when preceded by long runs of non-targets demonstrating that stimulus sequence is relevant for event-related components to both targets and non-targets. Results from the present study defined that both the pre-stimulus potential (RP amplitude and latency), event-related potentials (N200 and P300 latencies to targets, P300 amplitude for non-targets), and RT were significantly affected by the immediately preceding stimulus sequence. Changes in P300 amplitude for targets were of borderline significance ($P = 0.06$), most likely reflecting the limited analysis we could derive from the 60 target trials available for each subject. These brain potential changes have been taken as a sign of neural events related to short-term memory updating (Donchin and Coles 1988) and the resolution of subjective expectancies (Verleger 1988). The dramatic loss of the RP and the P300 components and the attenuation of N100 to non-targets immediately following targets compared to their relatively large amplitudes to non-targets immediately preceding the targets is compelling evidence of how rapidly such expectancies or memory updating can occur.

Sensory and cognitive components of the event-related potentials were not different as a function of instruction (button press or mental count) as has been previously reported (Barrett et al. 1987). When the potentials to targets in the button press condition were averaged relative to EMG onset several differences and similarities to the potentials averaged relative to stimulus onset were noted (Goodin et al. 1986). First, the N100 and P200 components were markedly attenuated in the response triggered averages compared to the stimulus triggered averages revealing how securely these components are temporally locked to the stimulus and not to the response. Thus their designation as sensory components is supported. Second, the amplitudes of the P300, and RP components were comparable in the two types of averages revealing that these components are temporally related to both the onset of the stimulus and to the onset of the EMG response. This result could be due to the relatively broad durations of the P300 (approximately 300 msec) and RP (500 msec) components such that the relatively narrow range of temporal variability between the onset of the stimulus and the onset of the EMG initiating the button press response (324 ± 47 msec) did not adversely affect P300 or RP amplitudes in the averaging process. In contrast, the N100 and P200, being of brief duration (< 100 msec), were seriously compromised in the response triggered averages. An alternative possibility is that the neural processes generating both the P300 and the RP are closely linked.

RT speeds have been shown to be related to the latency of certain of the event-related components, e.g., N200 and P300 (Ritter et al. 1979; Michalewski et al. 1986). When the latency of P300 and RT are closely related the tasks usually involve predictable stimulus processing (Kutas et al. 1977). When RT and the P300 component latency are decoupled, additional processing of the stimulus or the type of response is usually required (Duncan-Johnson and Kopell 1981). The task in the present study is of the former predictable type with stimuli appearing at a regular interval requiring a stereotyped motor response to a simple change (pitch) of a single stimulus feature. Correlations between RT and the various event-related components in the present study showed N200 latency particularly to be related to RT. This finding supports the identification of the N200 by Ritter et al. (1979) as a critical component in the decision processes classifying target and non-target stimuli. We also found that the RP amplitudes in both stimulus and response triggered averages were significantly correlated with RT documenting that neural processes *preceding* stimulus presentation are also likely to be involved in response preparation. The designation of the negative shift (labeled RP) as being solely related to the preparation to respond is incomplete since we have also shown that expectancy of the stimulus sequence independent of motor response may also play a role.

Supported by grants from the National Multiple Sclerosis Society RG 2414A1 and the National Institute of Allergy and Infectious Diseases No. AI-34250.

References

Barrett, G., Shibasaki, H. and Neshige, R. Cortical potentials preceding voluntary movement: evidence for three periods of preparation in man. Electroenceph. clin. Neurophysiol., 1986, 63: 327–339.

Barrett, G., Neshige, R. and Shibasaki, H. Human auditory and somatosensory event-related potentials, effects of response condition and age. Electroenceph. clin. Neurophysiol., 1987, 66: 409–437.

Brunia, C.H.M. and Damen, E.J.P. Distribution of slow brain potentials related to motor preparation and stimulus preparation in time estimation task. Electroenceph. clin. Neurophysiol., 1988, 69: 234–243.

Coles, M.G.H., Gratton, G. and Donchin, E. Detecting early communication using measures of movement-related potentials to illuminate information processing. Biol. Psychol., 1988, 26: 69–89.

Deecke, L. and Lang, W. P300 as the resolution of negative cortical DC shifts. Behav. Brain Sci., 1988, 11: 343–427.

Deecke, L., Scheid, P. and Kornhuber, H.H. Distribution of readiness potential, premotion positivity, and motor potential of the human cerebral cortex preceding voluntary finger movements. Exp. Brain Res., 1969, 7: 156–168.

Donchin, E. and Coles, M.G.H. Precommentary: is the P300 component a manifestation of context updating? Behav. Brain Sci., 1988, 11: 355–425.

Donchin, E., Tueting, P., Ritter, W., Kutas, M. and Heffley, E. On the independence of the CNV and P300 components of the human averaged evoked potential. Electroenceph. clin. Neurophysiol., 1975, 38: 449–461.

Duncan-Johnson, C.C. and Kopell, B.S. The Stroop effect: brain potentials localize the source of interference. Science, 1981, 214: 938–940.

Ghering, W.J., Gratton, G., Coles, M.G.C. and Donchin, E. Probability effects on stimulus evaluation and response processes. J. Exp. Psychol.: Hum. Percept. Perform., 1992, 18: 198–216.

Goodin, D.S., Squires, K.C. and Starr, A. Long-latency event-related components of the auditory evoked potentials in dementia. Brain, 1978, 44: 447–458.

Goodin, D.S., Squires, K.C. and Starr, A. Variations in early and late event-related components with task difficulty. Electroenceph. clin. Neurophysiol., 1983, 55: 680–686.

Goodin, D.S., Aminoff, M.J. and Mantle, M.M. Subclasses of event-related potentials: response-locked and stimulus-locked components. Ann. Neurol., 1986, 20: 603–609.

Goodin, D.S., Aminoff, M.J. and Ortiz, T.A. Expectancy and response strategy to sensory stimuli. Neurology, 1993, 43: 2139–2142.

Gratton, G., Coles, M.G.H. and Donchin, E. A new method for off-line removal of ocular artifact. Electroenceph. clin. Neurophysiol., 1983, 55: 468–484.

Gratton, G., Bosco, C.M., Kramer, A.F., Coles, M.G.H., Wickens, C.D. and Donchin, E. Event-related brain potentials as indices of information extraction and response priming. Electroenceph. clin. Neurophysiol., 1990, 75: 419–432.

Hardyck, C.D. and Petrinovich, L.F. Subvocal speech and comprehension level as a function of difficulty of level of reading material. J. Verb. Learn. Verb. Behav., 1970, 9: 647–652.

Hermanutz, M., Cohen, R. and Summer, W. The effects of serial order in long sequences on event-related potentials. Psychophysiology, 1981, 18: 415–423.

Hillyard, S.A. and Galambos, R. Effects of stimulus and response contingencies on a surface negative slow potential shift in man. Electroenceph. clin. Neurophysiol., 1967, 22: 297–304.

Johnson, Jr., R. and Donchin, E. Sequential expectancies and decision making in a changing environment: an electrophysiological approach. Psychophysiology, 1982, 19: 183–200.

Kitamura, J., Shibasaki, H. and Kondo, T. A cortical slow potential is larger before an isolated movement of a single finger than simultaneous movement of two fingers. Electroenceph. clin. Neurophysiol., 1993, 86: 252–258.

Kornhuber, H.H. and Deecke, L. Hirnpotentialänderungen bei Willkürbewegungen und passiven Bewegungen des Menschen: Bereitschaftspotential und reafferente Potentiale. Pflügers Arch. Ges. Physiol., 1965, 284: 1–17.

Kristeva, R., Cheyne, D., Lang, W., Lindinger, G. and Deecke, L. Movement-related potentials accompanying unilateral and bilateral finger movements with different inertial loads. Electroenceph. clin. Neurophysiol., 1990, 75: 410–418.

Kutas, M. and Donchin, E. Preparation to respond as manifested by movement related potentials. Brain Res., 1980, 202: 95–115.

Kutas, M., McCarthy, G. and Donchin, E. Augmenting mental chronometry. The P300 as a measure of stimulus evaluation time. Science, 1977, 197: 792–795.

Lang, W., Lang, M., Uhl, F., Kornhuber, A., Deecke, L. and Kornhuber, H.H. Left frontal lobe in verbal associative learning: a slow potential study. Exp. Brain Res., 1988, 71: 353–364.

McCallum, W.C. Potentials related to expectancy, preparation and motor activity. In: T.W. Picton (Ed.), Human Event-Related Potentials (EEG Handbook, Vol. 3). Elsevier, Amsterdam, 1988: 427–534.

Michalewski, H.J., Prasher, D.K. and Starr, A. Latency variability and temporal interrelationships of the auditory event-related potentials (N1, P2, N2, and P3) in normal subjects. Electroenceph. clin. Neurophysiol., 1986, 65: 59–71.

Ortiz, T.A., Goodin, D.S. and Aminoff, M.J. Neural processing in a three-choice reaction-time task: a study using cerebral evoked-potentials and single-trial analysis in normal humans. J. Neurophysiol., 1993, 69: 1499–1512.

Patterson, J., Michalewski, H.J. and Starr, A. Latency variability of the components of auditory event-related potentials to infrequent stimuli in aging, Alzheimer-type dementia, and depression. Electroenceph. clin. Neurophysiol., 1988, 71: 450–460.

Pfefferbaum, A., Ford, J.M., Wengart, B.G., Roth, W.T. and Kopell, B.S. Clinical application of the P3 component of event-related potentials. I. Normal aging. Electroenceph. clin. Neurophysiol., 1984, 59: 85–103.

Picton, T.W. The P300 wave of the human event-related potentials. J. Clin. Neurophysiol., 1992, 9: 456–479.

Polich, J., Howard, L. and Starr, A. Effects of age on the P300 component of the event-related potential from auditory stimuli: peak definition, variation and measurement. J. Gerontol., 1985, 6: 721–726.

Ragot, R. and Renault, B. P300 as a function of S-R compatibility and motor programming. Biol. Psychol., 1981, 12: 289–294.

Rebert, C.S. and Tecce, J.J. A summary of CNV and reaction times. In: W.C. McCallum and J.R. Knott (Eds.), The Responsive Brain. Wright and Sons, Bristol, 1980: 126–131.

Remington, R. Analysis of sequential effects in choice reaction times. J. Exp. Psychol., 1969, 82: 250–257.

Ritter, W., Simson, R. and Vaughan, Jr., H.G. Association cortex potentials and reaction time in auditory discrimination. Electroenceph. clin. Neurophysiol., 1972, 33: 547–555.

Ritter, W., Simson, R., Vaughan, Jr., H.G. and Friedman, D.A. A brain event related to the making of sensory discrimination. Science, 1979, 203: 1358–1361.

Ritter, W., Rotkin, L. and Vaughan, Jr., H.G. The modality specificity of the slow negative wave. Psychophysiology, 1980, 17: 222–227.

Rohrbaugh, J. and Gaillard, A.W.K. Sensory and motor aspects of CNV. In: A.W.K. Gaillard and W. Ritter (Eds.), Tutorials in ERP Research: Endogenous Components. Elsevier, Amsterdam, 1983: 269–310.

Rorhbaugh, J.W., Syndulko, K. and Lindsley, D.B. Brain wave com-

ponents of the contingent negative variation in humans. Science, 1976, 191: 1055–1057.

Rohrbaugh, J.W., Syndulko, K., Sanquist, T.F. and Lindsley, D.B. Synthesis of the contingent negative variation brain potential from noncontingent stimulus and motor elements. Science, 1980, 208: 1165–1168.

Roth, W., Ford, J. and Kopell, B. Long-latency evoked potentials and reaction times. Psychophysiology, 1978, 15: 17–23.

Ruchkin, D.S., Sutton, S., Mahaffey, D. and Glaser, J. Terminal CNV in the absence of motor response. Electroenceph. clin. Neurophysiol., 1986, 63: 445–463.

Squires, K.C., Wickens, C., Squires, N.K. and Donchin, E. The effect of stimulus sequence on the waveform of the cortical event-related potential. Science, 1976, 193: 1142–1146.

Sutton, S., Baren, M., Zubin, J. and John, E.R. Evoked potentials correlates of stimulus uncertainty. Science, 1965, 150: 1187–1188.

Tueting, P. and Sutton, S. The relationship between prestimulus negative shifts and poststimulus components of the averaged evoked potential. In: S. Kornblum (Ed.), Attention and Performance IV. Academic Press, New York, 1973: 185–207.

Tueting, P., Sutton, S. and Zubin, J. Quantifying evoked potential correlates of the probability of events. Psychophysiology, 1970, 7: 385–394.

Verleger, R. Event related potentials and cognition: a critique of the context updating hypothesis and an alternate interpretation. Behav. Brain Sci., 1988, 11: 343–427.

Walter, W.G., Cooper, R., Aldridge, V.J., McCallum, W.C. and Winter, A.L. Contingent negative variation: an electric sign of sensorimotor association and expectancy in the human brain. Nature, 1964, 203: 380–384.

Wise, R., Chollet, F., Hadar, U., Friston, K., Hoffner, E. and Frackowiak, R. Distribution of cortical neural networks involved in word comprehension and word retrieval. Brain, 1991, 114: 1803–1817.