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LA THÈSE A ÉTÉ
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THE EVENT-RELATED POTENTIALS RECORDED
DURING THE DISCRIMINATION OF IMPROBABLE STIMULI

© PETER G. FITZGERALD

Thesis presented to the School of Graduate Studies of
the University of Ottawa in partial fulfillment of
the requirements for the degree of Masters of Arts.

Ottawa, Canada, 1982

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UNIVERSITÉ D'OTTAWA
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PREFACE

The recording of event-related potentials, together with behavioural data, allows one a unique view of many complex processes in the human brain, of which signal discrimination is a fundamental component.

The research presented in this thesis is a direct attempt to solve a difficult question which had arisen as the result of an experiment carried out by myself and Dr. T.W. Picton in late 1979. This question involved the effects of target discriminability on the target-evoked potentials. In our experimental conditions the N2 component of the target-evoked potential increased in amplitude as target-discrimination difficulty was increased. The results of this initial experiment were reported at the Sixth International Conference on Event-related Slow Potentials of the Brain and the subsequent paper is contained in appendix A. These preliminary findings differed from the data recorded in the laboratory of Risto Naatanen which displayed larger N2 component amplitudes as the deviance of the target from the standard stimulus was increased. (or, in our terms, the target-discrimination difficulty was decreased). Naatanen and co-workers have postulated that the N2 component may represent a neuronal-mismatch process perhaps reflecting a central manifestation of the orienting reflex. This concept cannot explain our findings. A series of

experiments were therefore undertaken to resolve this controversy. The results of these experiments are presented in this thesis. The experiments provide an extensive examination of the effects of target-discrimination difficulty on the target-evoked potential in general, and the N2 component in particular.

An objective measure of stimulus discrimination difficulty would most certainly be an important tool in the investigation of human cognition. The development of such a measure would allow the effects of stimulus discriminability to be assessed in both applied and research settings. The N2 component of the target-evoked response is clearly sensitive to changes in stimulus discriminability and thus may provide this objective measure. Alterations in the amplitude and latency of the N2 component appear to reflect the operation of a modality non-specific frontal process involved in controlling the perceptual processes underlying stimulus evaluation. Recording the activity of the N2 component can provide an objective assessment of the effects of stimulus discriminability in a wide variety of circumstances.

The thesis has been written in the form of a publishable paper. The main body of the thesis has been formatted in accordance with the guidelines set by the journal, Biological Psychology, to which a revised copy will be submitted for publication.

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CURRICULUM STUDIORUM

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PUBLICATIONS:

Fitzgerald, P.G. and Picton, T.W. (1981). Temporal and sequential probability in evoked potential studies. Canadian Journal of Psychology, 35, 188-200.

Fitzgerald, P.G., Picton, T.W., Maru, J., Wolfe, R.G. and Campbell, K. (1982) Clinical evoked potential studies: III Pattern-reversal visual responses. Sensus, 1, 33-44.

Picton, T.W. and Fitzgerald, P.G. (in press). A general description of the human auditory evoked potentials. In: Moore, E.J. (Ed.). Bases of Auditory Brain Stem Evoked Responses. Grune and Stratton: New York.

Fitzgerald P.G. and Picton, T.W. (in press). The effects of probability and discriminability on the evoked potentials to unpredictable signals. In: Cohen, J., Karrer, R. and Teuting, P. (Eds.). Proceedings of the Sixth International Conference on Event-related Slow Potentials of the Brain.

ABSTRACT

The Event-related Potentials Recorded
During the Discrimination of Improbable Stimuli

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The ability to discriminate stimuli in the environment is a necessary and fundamental component of human cognition. Presently, our understanding of the psychological and neurophysiological processes involved in stimulus discrimination is incomplete. However, the technique of human event-related potential recordings has offered new investigative opportunity for the illumination of these complex processes.

In three separate experiments, subjects were required to detect improbable target stimuli which varied in frequency from an ongoing train of standard stimuli. Event-related potentials, time locked to the presentation of these stimuli, were recorded from the scalp in order to evaluate the effects of discrimination difficulty upon the component structure of these potentials. This evaluation, coupled with the results of behavioural data, allowed a detailed analysis of the processes underlying stimulus discrimination.

In the three conditions of experiment I, subjects were presented with two equally improbable target stimuli in a train of standard stimuli. The difficult target (1050 Hz) differed only slightly in frequency from the standard stimulus (1000 Hz), while the easy target (1500 Hz) was very different in frequency. The three conditions of the experiment involved either counting the targets, making a button press response to the targets, or ignoring the targets and reading a book.

Experiment II investigated the effects of discrimination difficulty using a range of four different targets, each equal in probability, rather than just one easy target and one difficult target.

Experiment III evaluated the effects of both target discriminability and probability on the target-evoked potentials in conditions requiring the subject to make a button press response to the targets, or ignoring the targets and reading a book.

The subjects in all three experiments consistently displayed a higher percentage of misses and delayed reaction times to the difficult target discriminations. Several components of the target-evoked response were found to vary as a function of the discriminability of the target stimulus. In comparison to the standard-evoked N1 component, the amplitude of the N1 to target stimuli increased as target discriminability was increased. The latencies of the target-evoked N2 and P3 components increased and the

amplitude of the P3 decreased as target discriminability was decreased. The key finding was the increase in N2 amplitude as the target discrimination became more difficult. Experiment III demonstrated that the amplitude of the N2 component, elicited by the easy target, was also enhanced by making the target highly improbable. This probability effect was not present for the N2 elicited by the difficult target stimulus.

Based upon the behavioural and evoked potential results, we have proposed a model of the processes underlying stimulus discrimination. This model consists of three overlapping stages. The first stage, labelled automatic processing, involves a passive mismatch comparison of incoming stimuli, and is reflected at the scalp by the N1 and N2a components. These components increase in amplitude as the target-discriminability (deviance from standard) is increased. The second stage, controlled processing, involves the evaluation of mismatched stimuli under the control of a modality non-specific frontal allocation process. This controlling process involves the allocation of effort to the evaluation of mismatched stimuli, and is reflected at the scalp by the N2b component. The more difficult the target-discrimination, the greater will be the allocation of effort to stimulus-evaluation and the longer this allocation will be sustained. The N2b component, reflecting the activity of this allocation process, would increase in amplitude and duration as target discriminability decreases.

The final stage of discrimination is composed of higher order control processes which function to modify (update) the parameters of the controlled processing stage, specifically, the allocation process. The degree of this modification activity is reflected at the scalp by the P3a, P3 and parietal slow wave components.

TABLE OF CONTENTS

Section	page
PREFACE.....	ii
ACKNOWLEDGEMENTS.....	iv
CURRICULUM STUDIORUM.....	v
ABSTRACT.....	vi
1. INTRODUCTION.....	1
2. METHODS.....	4
2.1 Subjects.....	4
2.2 Stimuli.....	4
2.3 Experiment I procedure.....	5
2.4 Experiment II procedure.....	6
2.5 Experiment III procedure.....	6
2.6 Recording.....	7
2.7 Reaction times.....	9
2.8 Data analysis.....	9
3. RESULTS.....	11
3.1 Experiment I.....	11
3.2 Experiment II.....	15
3.3 Experiment III.....	17
a. Attend conditions.....	19
b. Attend-Read Comparisons.....	21
c. Read conditions.....	22
4. DISCUSSION.....	24
4.1 Experiment I.....	24
4.2 Experiment II.....	32
4.3 Experiment III.....	35
4.4 General discussion.....	37
5. CONCLUSION.....	48
REFERENCES.....	49
APPENDIX A.....	75

LIST OF TABLES

Table		page
1	Mean amplitude and latency measures for the N2, P3 and P3a components in conditions A, B and C of Experiment I.....	57
2	Mean amplitude and latency measures for the N2 and P3 components in Experiment II.....	58
3	Mean amplitude and latency measures for the N2 and P3 components in conditions A and B of Experiment III.....	59
4	Mean amplitude and latency measures for the N2 and P3a components in conditions C and D of Experiment III.....	60
5	Review of stimulus parameters and effects recorded for selected studies concerned with signal discrimination.....	61
	Explanatory notes for Table 5.....	62

LIST OF FIGURES

Figure		page
1	Grand-mean target-evoked potentials for the 12 subjects, recorded from Fz, Cz, Pz, C3 and C4 electrodes in condition A (count) of experiment I.....	67
2	Grand-mean target-evoked potentials for the 12 subjects, recorded from Fz, Cz, Pz, C3 and C4 electrodes in condition B (respond) of experiment I.....	68
3	Grand-mean target-evoked potentials for the 12 subjects, recorded from Fz, Cz, Pz, C3 and C4 electrodes in condition C (read) of experiment I.....	69
4	Target-evoked potentials for subject BB, recorded from Fz, Cz, Pz, C3 and C4 electrodes in condition A (count) of experiment I.....	70
5	Grand-mean target and standard-evoked potentials for the 10 subjects, recorded from Fz, Cz and Pz electrodes in experiment II.....	71
6	Grand-mean 1025 Hz target and 1000 Hz standard-evoked potentials for the 10 subjects, recorded from Fz, Cz and Pz electrodes in experiment II.....	72
7	Grand-mean target-evoked potentials for the 8 subjects, recorded from Fz, Cz and Pz electrodes in the attend conditions of experiment III.....	73
8	Grand-mean target-evoked potentials for the 8 subjects, recorded from Fz, Cz and Pz electrodes in the read conditions of experiment III.....	74

1. INTRODUCTION

The event-related potentials (ERPs) evoked by infrequent and unpredictable "target" stimuli in a train of "standard" stimuli have been extensively investigated (Squires, Squires and Hillyard, 1975; Ford, Roth and Kopell, 1976; Goodin, Squires, Henderson and Starr, 1978; Rohrbaugh, Syndulko and Lindsley, 1978; Ritter, Simson, Vaughan and Friedman, 1979; Naatanen, Hukkanen and Jarvilehto, 1980; Fitzgerald and Picton, in press). When the target stimulus is more difficult to discriminate there is an increase in the latencies of both the N2 and P3 components of the response and a reduction in P3 amplitude. These latency changes for the N2 and P3 components have been related to the longer time required for stimulus evaluation when the signal is difficult to discriminate (Donchin, 1979; Ritter et al., 1979; Duncan-Johnson and Donchin, 1982). The reduction in P3 amplitude may be attributed to what Ruchkin and Sutton (1978b) call "equivocation", or the effective loss of information due to the subject's uncertainty about having perceived an event.

There are no consistent changes reported for the N2-amplitude with increasing difficulty of target-discrimination. Ford et al. (1976) compared N2-amplitudes across increasingly difficult target-discriminations and found no significant differences, although there was a small

trend for increasing N2-amplitudes with easier target-discriminations. Naatanen et al. (1980) found that N2-amplitude was larger the greater the deviation of the target from the standard (i.e. the easier the target-discrimination). Fitzgerald and Picton, (in press) and Campbell, Marois and Arcand (in press) found that the N2-amplitude increased significantly as target discriminability decreased. In both these latter studies, however, the easy and difficult discriminations occurred in separate conditions. The amount of effort devoted to the discrimination may therefore have varied between the two conditions.

An N2-P3a complex can be evoked by infrequent deviant stimuli in non-attending subjects (Squires et al., 1975; Snyder and Hillyard, 1976; Naatanen, Simson and Loveless, 1982). The relationship of this N2-P3a complex to the late components (N2, P3) evoked by infrequent targets in attending subjects is not fully known.

This paper presents the results of three experiments which investigated the effects of target-discrimination difficulty on the event-related potentials. In all three experiments both the easy and difficult target-discriminations were in the same condition, and reaction times were recorded in order to evaluate the actual difficulty of the perceptual discriminations. Experiment I evaluated the effects of a difficult vs easy target-discrimination when the subjects counted the targets, made a button press

response to the detected targets, and ignored the targets and read a book. Experiment II evaluated the effects of discrimination difficulty using a range of four different targets rather than just one easy target and one difficult target. In Experiment III, the effects of both target discriminability and probability on the target-evoked potential were investigated in both attending and reading conditions.

2. METHODS

2.1. Subjects

Of the nineteen subjects, ten were male and nine were female. Their ages ranged from 17 to 37 years. All subjects were right-handed and screened for normal hearing using 1000 Hz tones of 20 dB ISO. Twelve subjects participated in the first experiment, ten in the second and eight in the third. Four subjects participated in all three experiments, one subject participated in only the first and second, and two subjects in only the first and third. For the experiments, the subjects sat quietly in a comfortable reclining chair in a quiet room.

2.2. Stimuli

Tonebursts with rise and fall times of 5 msec each and a total duration of 55 msec were generated using either Tektronics FG501 or Wavetek 159 function generators and Grason-Stadler 1200 series logic. Tonebursts ranging in frequency from 1000 to 1800 Hz were presented through TDH-49 earphones to the right ear of the subject. The intensity of all tonebursts was 80 dB peak SPL as measured on a Bruel & Kjaer model 2209 sound level meter with a type 4152 artificial ear. For tonebursts of this duration, and of the frequencies used, this represents an intensity of approximately 65 dB SL. The random sequencing of stimuli, the inter-

stimulus interval and the total number of stimuli in each block was controlled by a MINC-11 computer.

2.3. Experiment I Procedure

This experiment was composed of three separate conditions, the order of which was balanced across subjects. Tones were presented at a rate of 1.1/sec, 80% of the stimuli being 1000 Hz tones, 10% 1500 Hz tones and 10% 1050 Hz tones. Both improbable stimuli were designated as 'targets' and the more probable stimuli as 'standards'. In condition A (counting) the subjects were instructed to detect and keep a running mental count of all targets (i.e. to count both 1500 Hz (easy) and 1050 Hz (difficult) targets together). At the end of each block the experimenter recorded the subjects tally and commented on its accuracy. In condition B (responding) the subjects were instructed to press a micro-switch button (with the index finger of their right hand) upon detection of either target stimulus. In condition C (reading) the subjects were instructed to read a novel and to ignore the stimuli. The horizontal EOG was monitored to ensure subjects read throughout the duration of each block. Conditions A and B consisted of four blocks of approximately 330 stimuli and condition C consisted of five blocks. More stimuli were used for the reading condition because of the greater number of eye movement artifacts.

2.4. Experiment II Procedure

Ten blocks of approximately 300 stimuli were presented at an inter-stimulus interval of 1.1 sec. Within each block of stimuli, 80% of the stimuli were 1000 Hz tones, 5% were 1500 Hz tones, 5% were 1100 Hz tones, 5% were 1050 Hz tones and 5% were 1025 Hz tones. The four improbable stimuli were designated as 'targets' and the 80% probable stimuli as 'standards'. The subjects were instructed to press a micro-switch button (with the index finger of their right hand) upon detection of any target stimulus.

2.5. Experiment III Procedure

In this experiment four separate conditions were used. All conditions contained seven blocks of approximately 330 stimuli presented at an inter-stimulus interval of 1.1 sec. Three different targets were used in each condition, but the probability of the targets and the task of the subject varied between conditions. In conditions A and C (improbable-difficult), 80.5% of the stimuli were 1000 Hz tones, 13.5% were 1800 Hz tones, 4.5% were 1200 Hz tones and 1.5% were 1050 Hz tones. In conditions B and D (probable-difficult), 80.5% of the stimuli were 1000 Hz tones, 13.5% were 1050 Hz tones, 4.5% were 1200 Hz tones and 1.5% were 1800 Hz tones.

In conditions A and B the three improbable stimuli were designated as 'targets' and the more probable stimuli as 'standards'. The subjects were instructed to press a

micro-switch button (with the index finger of their right hand) upon the detection of any target stimulus. In conditions C and D the subjects were instructed to read a novel and to ignore the stimuli. The horizontal EOG was monitored to ensure subjects read throughout the duration of each block. The ordering of conditions was such that a subject would either start with condition A and finish with condition B or vice versa. This allowed the subjects to read for a sustained period of time rather than for multiple shorter periods. With consideration of the above rule, the ordering of conditions was balanced across subjects.

2.6. Recording

Electroencephalographic (EEG) signals were recorded from Fz, Cz, Pz, C3 and C4 scalp locations (10-20 system) using Beckman Ag/AgCl electrodes connected to the scalp using Beckman saline paste, adhesive collars and collodion-impregnated gauze (Picton, Woods and Proulx, 1978a). Right and left mastoid electrodes linked at the center-point of a 20 kOhm resistor served as the reference for the scalp EEG recordings. A vertical electrooculogram (EOG) was recorded from electrodes placed on the upper and lower ridges of the left eye, and in experiments I and III a horizontal EOG was also recorded between electrodes placed at the external canthi. The inter-electrode impedances were below 5 kOhms at 20 Hz. EEG and EOG signals were amplified on Beckman R-611 polygraph amplifiers modified to have a 6.6

sec time constant and a high frequency cut-off of 100 Hz. The amplified EEG and EOG signals were digitized at dwell-times of 4.5 msec over a 900 msec sweep beginning 50 msec prior to the stimulus. Using the MINC-11, digitized single-trial data were coded and stored on disk or magnetic-tape for subsequent off-line averaging. In experiments II and III all single trial data were coded and separately averaged as hit or miss, according to the presence or absence of a button press response. This classification by response was not carried out in experiment I. Any trial with an EEG or EOG voltage of greater than ± 100 μ V was rejected from the averaging process. The average evoked potential waveforms for each subject were written out on a Tektronics 4662 X-Y plotter, and stored on floppy diskettes. In experiment III there were a large number of small lateral eye movements that were not rejected using the ± 100 μ V limits. The effects of the eye-movements on the EEG recordings were determined for each subject and for each EEG recording site. Any averaged evoked potential with an accompanying EOG average of greater than 10 μ V was then EOG compensated by subtracting from each channel of averaged EEG data the effects of the EOG (cf. Verleger, Gasser and Mocks, 1982).

In experiment I, difference-waveforms were obtained by either subtracting the average evoked potential to the standard stimulus from that to the target stimulus within a condition (cf. Simson, Vaughan and Ritter, 1977a), or by subtracting the averaged evoked potential to the target

stimulus in condition C (reading) from that to the corresponding target stimulus in condition A (count) (cf. Goodin et al., 1978).

2.7. Reaction times

Reaction times were measured in all attend conditions with the exception of condition A (count) in experiment I. A reaction time was accepted if it occurred within 100-850 msec after stimulus onset. A reaction time histogram was calculated using 13.5 msec bins and plotted such that the vertical scale in percentage responses was equal to the vertical scale in uV of the evoked potential waveform. The means and standard deviations of the reaction times were also calculated.

2.8. Data Analysis

Peak components were identified within the following latency ranges: N1, 65-140 msec; P2, 130-230 msec; N2, 180-350 msec; P3, 250-600 msec; SW, 400-800 msec. For the reading conditions of experiments I and III a P3a component was identified within the latency range 220-350 msec (Squires et al., 1975). The N1, P2, N2, P3 and P3a components were identified at the Cz location, and amplitude measures at the other electrodes were made at the Cz latency. The Slow Wave (SW) component was measured at the latency of the peak negativity at Fz. The amplitudes were measured relative to the mean value of the waveform in the 50 msec

prior to the stimulus. All measurements were evaluated using repeated measures analyses of variance. Unless otherwise stated, results are reported as significant at $p < 0.01$.

3. RESULTS

3.1. Experiment I

In condition A the mean absolute percentage error in the subjects' counts was 8%. These errors were mainly omissions. In condition B the subjects missed on average 20% of the 1050 Hz targets (difficult) and 2% of the 1500 Hz targets (easy); this difference being significant. There was a significantly later mean reaction time to the 1050 Hz target (497 msec $\pm$ 122) as compared to the 1500 Hz target (401 msec $\pm$ 104). In condition C all subjects reported that they had read continuously and had not attended to the stimuli.

Grand-mean target-evoked potentials for the three experimental conditions are shown in Figures 1, 2 and 3. In conditions A and B the evoked potential waveforms elicited by standard stimuli (1000 Hz) consisted of N1-P2-N2 components. The evoked potential waveforms elicited by the target stimuli (1050 Hz, 1500 Hz) consisted of N1-P2-N2-P3-SW components. In condition C the evoked potential waveforms elicited by standard and target stimuli contained N1-P2-N2 components. However, the evoked potential to the 1500 Hz target also contained a small P3a component.

Figures 1, 2 and 3

In conditions A and B the N1 components elicited by

the 1050 Hz target (-4.1 uV at Cz) and by the 1000 Hz standards (-3.8 uV) were significantly smaller than those elicited by the 1500 Hz target stimuli (-5.0 uV). There were no significant amplitude differences between the N1 components elicited by the 1050 Hz target and the 1000 Hz standard stimuli. The N1 was maximally recorded centrally (on average, Fz/Cz = 88%, Pz/Cz = 72%), and its scalp distribution did not change significantly across stimulus type or conditions. The overall average latency of the N1 component was 94 msec. Latency did not change significantly across stimulus type or conditions.

The P2 component was small (on average 1.1 uV at Cz) and quite variable in amplitude. There were no significant changes in its amplitude or latency across conditions or stimulus type. Its overall average latency was 174 msec.

The average N2 and P3 amplitudes and latencies for conditions A and B are given in Table 1. There were no significant differences in these measurements between conditions A and B. In both conditions the N2 component was significantly larger (-3.5 uV at Cz) to the 1050 Hz (difficult) target than to the 1500 Hz (easy) target (-1.0 uV at Cz). The ANOVA results comparing the 1050 Hz and 1500 Hz targets showed at the Cz, Pz, and C4 electrodes a significance level of $p < 0.025$, while at Fz and C3 the level was $p < 0.01$. The latency of the N2 component was significantly later to the 1050 Hz target (294 msec) than to the 1500 Hz

target (233 msec) in both conditions A and B. The N2 to the standard stimulus had a mean latency of 311 msec.

For all three conditions the N2 was maximally recorded frontally for all target stimuli. The standard-evoked N2 was recorded equal in amplitude at Fz and Cz in condition A, Fz maximum in condition B, and Cz maximum in condition C. In condition C (read) the N2 occurred at an average latency of 256 msec for the 1050 Hz target with an average amplitude at Cz of -3.0 uV, and at an average latency of 290 msec for the 1000 Hz standard, which displayed an average amplitude at Cz of -2.3 uV. These latency and amplitude differences between the 1050 Hz target and the 1000 Hz standard were not significant. There was a tendency for the N2 elicited by the 1500 Hz target to be smaller in amplitude (on average -1.3 uV at Cz) and earlier in latency (215 msec) in comparison to the other two stimulus types.

One subject detected far fewer 1050 Hz (difficult) targets than the other subjects. His mean percentage error in condition A was 20%, and in condition B he missed 32% of the 1050 Hz targets and 1% of the 1500 Hz targets. This subject did not display the characteristic increase in N2 amplitude for the 1050 Hz (difficult) target stimuli. His target-evoked potentials for condition A are shown in Figure 4. When this subject was omitted from the analysis, the difference in N2 amplitude between the 1050 Hz and 1500 Hz targets reached a significance level of $p < 0.01$ at Fz Cz and Pz, and a level of $p < 0.001$ at C3 and C4.

Figure 4

The two subtraction techniques (target-standard and attend-ignore) were used to evaluate the N2 amplitude in condition A. There were no significant differences in N2 amplitude between 1050 Hz and 1500 Hz targets evaluated by either subtraction method.

In conditions A and B the P3 component to the 1050 Hz (difficult) target stimulus was significantly smaller in amplitude and later in latency than to the 1500 Hz (easy) target stimulus. The P3 component was recorded maximally at the Pz electrode for both the 1500 Hz target (Pz/Cz = 138%) and the 1050 Hz target (Pz/Cz = 240%); the 1050 Hz target evoking a significantly more parietal P3 than the 1500 Hz target. Across conditions A and B the average P3 latency for the 1500 Hz target was 337 msec and for the 1050 Hz target was 443 msec; this difference being significant. In condition C a P3a was recorded with maximum amplitude at the central electrodes in response to the 1500 Hz target (Table 1). Its average amplitude at Cz was 1.0 uV and its average latency was 262 msec. No such component was recognizable in the response to the 1050 Hz target.

The SW component was recorded as a negativity anteriorly and as a positivity posteriorly. Across conditions A and B the SW component did not change significantly in amplitude and it did not discriminate between the 1050 Hz

and 1500 Hz target stimuli. However, both targets evoked significantly larger SW components than the standard stimuli. No consistent SW activity was recorded to any stimuli in condition C.

3.2. Experiment II

In this experiment the subjects missed on average 70.5% of the 1025 Hz targets, 27.6% of the 1050 Hz targets, 15.8% of the 1100 Hz targets and 1.8% of the 1500 Hz targets. This trend of increasing number of misses for the more difficult target discriminations was significant ($p < 0.001$). The mean reaction times and standard deviations for the target stimuli were: 1025 Hz - 531 msec $\pm$ 122, 1050 Hz - 462 msec $\pm$ 123, 1100 Hz - 417 msec $\pm$ 107 and 1500 Hz - 357 msec $\pm$ 88. There was a significant decrease in the reaction time and in its variability as the target discrimination became easier. Subjects also responded (false alarms) on average to 0.5% of the standard stimuli.

Grand-mean evoked potential waveforms are shown in Figure 5, along with the respective reaction time histograms for each target stimulus. The evoked potential waveforms elicited by standard stimuli (1000 Hz) and missed 1025 Hz targets consisted of N1-P2-N2 components (see Figure 6). The evoked potential waveforms elicited by the detected (hit) target stimuli consisted of N1-P2-N2-P3-SW components. SW activity was not evaluated and data recorded from C3 and C4 electrodes were not analyzed in this experiment.

Figure 5

The N1 component was maximally recorded centrally, and was largest in amplitude to the 1500 Hz target (-6.8 uV at Cz) and smallest to the standard stimulus (-4.8 uV). The N1 component elicited by the 1500 Hz target was significantly larger in comparison to that elicited by the standard stimulus. However, in analysing the N1 components elicited by the various target stimuli, there were no significant amplitude differences. The latency of the N1 component (on average 98 msec) was also not significantly affected by the change in frequency of the target stimuli.

As in experiment I, the P2 component was small in amplitude. However, P2 was significantly larger in amplitude and later in latency at Cz for the target stimuli closer in frequency to the standard. The average P2 amplitudes and latencies for the various target stimuli at Cz were: 1025 Hz, 2.6 uV at 186 msec; 1050 Hz, 1.2 uV at 182 msec; 1100 Hz, 0.5 uV at 177 msec; and 1500 Hz, -0.4 uV at 164 msec. The P2 to the 1000 Hz standard had an amplitude at Cz of 2.8 uV and a latency of 190 msec.

The average N2 and P3 amplitudes and latencies are given in Table 2. At the Fz and Cz electrodes there was a significant increase in N2 amplitude and latency as a function of the target stimuli being closer in frequency to that of the standard stimulus (i.e. the discrimination being more difficult). The N2 component was maximally recorded

frontally for all stimulus types, decreasing in amplitude from anterior to posterior regions. The N2 elicited by the standard stimulus was small in amplitude (an average -1.6 μV at Cz) and somewhat late in latency (305 msec).

The P3 component at Fz, Cz and Pz was significantly smaller in amplitude, and later in latency to the more difficult to detect target stimuli. The P3 component was maximally recorded parietally for all target stimulus types with the target stimuli closer in frequency to the standard tending to evoke a more parietal P3 component.

A statistical analysis of the hit vs miss 1025 Hz target evoked potentials was not carried out. However, as shown in Figure 6, there are marked differences in the responses. The evoked potential waveform elicited by the missed 1025 Hz target displays little N2 activity. Thus the averaging of all 1025 Hz target stimuli, regardless of response classification (hit/miss), as in experiment I, would have decreased the N2 amplitude to the 'hit' 1025 Hz target waveform. It is interesting to note that there are also N2 and P3 components (similar to those elicited by detected 1025 Hz targets) recorded to the standard stimuli which were responded to (false alarms), presumably as 1025 Hz targets.

Figure 6

3.3. Experiment III

In condition A (improbable-difficult) the subjects

missed on average 16% of the 1050 Hz targets, 2% of the 1200 Hz and 0.9% of the 1800 Hz targets. In condition B (probable-difficult) the subjects missed on average 25% of the 1050 Hz targets, 2.6% of the 1200 Hz and 0.9% of the 1800 Hz targets. In both conditions A and B there were significantly more misses for the more difficult target discriminations. There were no significant differences in the number of misses between the two conditions. The mean reaction times for the target stimuli in condition A were; 1050 Hz - 490 +/-119, 1200 Hz - 404 +/-149, and 1800 Hz - 337 +/-90. In condition B the mean reaction times were; 1050 Hz - 459 +/-127, 1200 Hz - 373 +/-110, and 1800 Hz - 343 +/-89. In both conditions A and B the easier target-discriminations had significantly earlier and less variable reaction times. There were no significant differences in reaction time across the two conditions. In conditions C and D all subjects reported that they had read continuously and had not attended to the stimuli.

Grand-mean evoked potential waveforms for the four experimental conditions are shown in Figures 7 and 8. In conditions A and B the evoked potential waveforms elicited by standard stimuli (1000 Hz) consisted of N1-P2-N2 components. The evoked potential waveforms elicited by the target stimuli (1050 Hz, 1200 Hz and 1800 Hz) consisted of N1-P2-N2-P3-SW components. The SW component was not evaluated and data recorded from C3 and C4 electrodes was not analyzed in this experiment. In conditions C and D the evoked potential

waveforms elicited by standard and target stimuli contained N1-P2-N2 components. A distinct P3a component was present following some target stimuli.

 Figures 7 and 8

a. Attend Conditions

Initial comparisons were made between conditions A and B using the 1200 Hz target stimulus which was presented at the same probability in both conditions. There were no significant differences in amplitude or latency for any of the components at any scalp electrode sites. Thus, comparisons were done across conditions A and B under the assumption that there were no significant general state differences between the two conditions.

Of particular interest were the N2 and P3 components elicited by the 1050 Hz and 1800 Hz target stimuli in conditions A and B. Analyses were carried out to evaluate the effects of discriminability independently of probability: 1050 Hz - 1.5% (condition A) vs 1800 Hz - 1.5% (condition B), and 1800 Hz - 13.5% (condition A) vs 1050 Hz - 13.5% (condition B). The effects of probability were then evaluated independently of discriminability: 1050 Hz - 1.5% (condition A) vs 1050 Hz - 13.5% (condition B), and 1800 Hz - 13.5% (condition A) vs 1800 Hz - 1.5% (condition B). The average N2 and P3 amplitudes and latencies for these comparisons are shown in Table 3. As in experiments I and II, the N2 component was maximally recorded frontally and the

P3 component maximally recorded parietally for all target stimuli.

N2 - effects of discriminability:

There were no significant differences in the amplitude of the N2 component elicited by the 1050 Hz target in condition A and the 1800 Hz target in condition B (both 1.5%). However, the 1050 Hz target was significantly later in latency (258 msec) as compared to the 1800 Hz target (185 msec). The N2 component elicited by the 1800 Hz target in condition A was significantly smaller compared to the 1050 Hz target in condition B (both 13.5%) (Fz, $p < 0.01$; Cz, $p < 0.025$). In this comparison the latency of the N2 component was again significantly later to the 1050 Hz target (252 msec) as compared to the 1800 Hz target (198 msec).

N2 - effects of probability:

There were no significant differences in N2 amplitude or latency between the 1050 Hz target stimuli in conditions A and B. The N2 component to the 1800 Hz target in condition B (1.5%) was larger at all electrodes as compared to the 1800 Hz target in condition A (13.5%); although this comparison did not reach a significance level of $p < 0.01$ (Pz was $p < 0.025$). There were no significant differences in N2 latency between the 1800 Hz target in conditions A and B.

P3 - effects of discriminability:

In comparing the 1050 Hz target in condition A to the 1800 Hz target in condition B (both 1.5%) there was a tendency (Fz, $p < 0.025$ and Cz, $p < 0.05$) for the P3 component

to be larger to the 1800 Hz target. The latency for the P3 was earlier to the 1800 Hz target (298 msec) as compared to the 1050 Hz target (376 msec). The P3 component elicited by the 1800 Hz target in condition A was significantly larger in amplitude as compared to the 1050 Hz target in condition B (both 13.5 %). Again the latency of the P3 was earlier to the 1800 Hz target (301 msec) as compared to the 1050 Hz target (377 msec).

P3 - effects of probability:

There was a tendency (Cz, $p < 0.025$ and Pz, $p < 0.05$) for the P3 component elicited by the 1050 Hz target in condition A (1.5%) to be larger in amplitude as compared to condition B (13.5%). There was no significant P3 latency differences in comparing the 1050 Hz target in the two conditions. The P3 component elicited by the 1800 Hz target in condition B (1.5%) was significantly larger in amplitude as compared to the 1800 Hz target in condition A (13.5%). P3 Latency was unaffected by the probability change in the 1800 Hz target across conditions A and B.

b4 Attend-Read Comparisons

Evaluating the effects of attention (i.e. condition A vs C, and condition B vs D) on the N1-P2 components revealed no significant changes in amplitude or latency. The target-evoked N2 and P3 components were much larger in the attend conditions, as would be expected. Analysis of the N2 component elicited by standard stimuli in the attend and

read conditions showed that the N2 had a significantly more frontal scalp distribution in attend conditions.

c. Read Conditions

For the reading conditions C and D, the N2 and P3a components were of particular interest. Analyses were done across conditions C and D in a similar fashion to the attend conditions. Comparisons made in this manner allowed for the control of the effects of either target discriminability or target probability. The average N2 and P3a amplitudes and latencies are given in Table 4. Generally, the N2 and P3a components were small in amplitude and quite variable. The P3a was generally not well elicited by the probable targets and/or targets close in frequency to the 1000 Hz standard stimulus. For all comparisons made in the reading conditions, none were significant at the $p < 0.01$ level. However, several consistent trends exist in the data and they are reviewed below.

N2 - effects of discriminability:

The N2 component was maximally recorded frontally for all target stimuli. There were no significant amplitude differences in the N2 elicited by the 1050 Hz target in condition C and the 1800 Hz target in condition D (both 1.5%); although these targets did elicit the largest N2 components for the respective conditions. No significant amplitude differences for the N2 elicited by the 13.5% targets in the two conditions were present.

N2 - effects of probability:

In comparing the effects of probability on the N2 elicited by the 1050 Hz target in condition C (1.5%) to the N2 elicited by the 1050 Hz target in condition D (13.5%), the former displayed a larger N2 ($p < 0.1$ at Fz, Cz). The N2 to the 1800 Hz target in condition D (1.5%) was larger in amplitude as compared to the 1800 Hz target in condition C (13.5%), but the effect was variable and not significant.

P3a - effects of discriminability:

The P3a component was maximally recorded centrally for all target stimuli. The P3a elicited by the 1800 Hz target in condition D was larger in amplitude, as measured at Cz, than the P3a to the 1050 Hz target in condition C ($p < 0.1$) (both 1.5%). The P3a components elicited by the 1800 Hz target in condition C and by the 1050 Hz target in condition D (both 13.5%) were not significantly different.

P3a - effects of probability:

The 1800 Hz target in condition D (1.5%) elicited a larger P3a than the 1800 Hz target in condition C (13.5%); the comparison having a significance level of $p < 0.1$ at Cz. The 1050 Hz target in conditions C and D elicited little P3a activity and no significant differences were present.

4. DISCUSSION

The results of each experiment will be discussed first. A general discussion will follow.

4.1. Experiment I

This experiment was designed to evaluate the effects of discrimination difficulty on the evoked potentials to target stimuli when both difficult and easy targets were presented in the same block of stimuli. The results showed that changes in the target-discriminability are clearly related to specific changes in the N1, N2, P3 and P3a components of the target-evoked potentials. The design of this experiment closely replicates that of Naatanen et al. (1980) with three exceptions (Table 5). They used stimuli of a longer duration (150 msec instead of 55 msec) presented at shorter inter-stimulus intervals (0.84 sec instead of 1.1 sec) and targets that were less probable (5% instead of 10%).

N1 component:

The amplitude of the target-evoked N1 component was smaller when the frequency of the target was closer to that of the more probable standard stimulus. This may be explained by the N1 component having a refractory period of approximately 10 sec (Davis, Mast, Yoshie, and Zerlin, 1966; Nelson and Lassman, 1968) and by the frequency specificity

of this refractory period (Butler, 1968; Picton, Hillyard and Galambos, 1976; Picton, Woods, and Proulx, 1978b). The improbable targets usually followed a series of standard stimuli which differed in frequency from the targets, whereas the standard stimuli usually followed a series of other standard stimuli. This overall effect was greater for the 1500 Hz target stimulus which was appreciably further in frequency from the standard stimulus (1000 Hz) than the 1050 Hz target stimulus.

Butler (1968) postulated a neuronal habituation model to account for the frequency-specific refractory period of the N1. He proposed that there was an overlap in the neural populations activated by stimuli of similar frequency, and that this overlap decreased as the frequency separation between two stimuli increased. The reduction in N1 amplitude with stimulus repetition would be greatest when the same neural units were repeatedly activated by stimuli of identical frequency, and least when new neural units were "brought into play" by stimuli of a different frequency. In our experiment the 1500 Hz target elicited a larger N1 than the 1050 Hz target because it had a smaller number of neural units in common with the 1000 Hz standard stimulus.

Naatanen et al. (1980) and Naatanen et al. (1982) suggested that the enhancement of N1-amplitude to stimuli much removed in frequency from the standard stimulus could be the result of the early onset of a mismatch N2 component. We did not observe, however, any widening of the N1 compon-

ent or attenuation of the P2 component in the response to the easy targets. Also, there were no differences in the scalp distribution of the N1 component between target and standard stimuli that might have been caused by an overlapping mismatch N2. The N1, therefore, appears to be the first metric of stimulus deviance in the evoked potential. This measure of stimulus deviance appears to be task independent, since it is similar when the stimuli are attended or ignored.

N2 component:

The N2 component was maximally recorded anteriorly. It had a longer peak latency and a larger amplitude when the target was more difficult to discriminate. The latency changes agree with previous studies altering target-discriminability (Ford et al., 1976; Naatanen et al., 1980; Ritter et al., 1979; Fitzgerald and Picton, in press; Campbell et al., in press). The increase in N2 amplitude for the more difficult target-discriminations replicates our previous findings (Fitzgerald and Picton, in press) and those of Ritter et al., (1979), Campbell et al., (in press) and Goodin, Squires and Starr (unpublished manuscript, 1979). However, Naatanen et al. (1980) have reported opposite results, and Ford et al. (1976) also report a trend opposite to what we have recorded.

Two factors may have affected the amplitude of the N2 component in all of these experiments. First, the timing of the discriminations was probably more variable for the more

difficult targets. The reaction times clearly displayed increased variability for the difficult discriminations. A latency-jitter in the endogenous components may have decreased the recorded N2-amplitude. Second, the N2 to the missed signals (mostly 1050 Hz targets) was probably absent or smaller than the N2 to the detected signals (see section 4.2). Thus, averaging missed and detected signals together could have reduced the recorded N2 amplitude. This could explain the responses of the subject who missed 20% of the targets in this experiment (Figure 4). This subject had a larger N2 component to the easy target (-7.8 uV) than to the difficult (-5.4 uV). If one assumes, however, that 90% of his errors were due to missing difficult targets, 36% of his evoked responses to difficult targets would have had small or absent N2 components. The N2 to the detected difficult target could therefore have been as large as $-5.4/.64$ or -8.4 uV.

Both these factors would have had more effect on the responses to the difficult targets and decreased the probability of our recording the differences in N2 amplitude that we actually obtained. The latency factor might have been decreased by techniques that compensate for latency variability (Woody, 1967; Ruchkin, McCalley and Glaser, 1977), but unfortunately the N2 component is smaller than other components in the response, such as the P3 wave which would dominate any latency-compensation procedures. The second factor could have been decreased by separately

averaging the responses to detected and missed targets. This was done in the subsequent experiments.

The evaluation of N2 amplitudes in the subtraction-waveforms was complicated by the occurrence of several different components in the N2 latency range. When subtracting the response to the ignored 1500 Hz target from that to the attended 1500 Hz target as done by Goodin et al. (1978; unpublished manuscript, 1979) the P3a component (latency 262 msec) in the response to the ignored target artificially increased the amplitude of the N2 component (latency 236 msec) in the difference waveform. Two slightly different problems occur when subtracting the responses to the targets from those to the standard stimuli in the same condition (cf. Simson et al., 1977a). The N2 to the 1050 Hz target occurs at the same latency as the N2 to the standard stimulus, whereas the N2 to the 1500 Hz target occurs at the same latency as the end of the P2 component to the standard stimulus. The subtraction-technique assumes that the stimulus-determined N1-P2-N2 complex is the same for the targets and for the standard stimuli. It is quite possible that the exogenous P2-N2 components of the response to the targets are different from those to the standard stimuli. If they were absent in the target-response, subtracting standard from target waveforms would artificially enhance the N2 component that occurs at the latency of the standard P2 and artificially reduce the N2 that occurs at the latency of the standard N2. Furthermore, because of frequency-

specific refractory effects the assumption that the exogenous N1-P2-N2 complex of the response is equivalent for targets of different frequencies is even less valid. The exogenous P2-N2 components may have been larger for the more deviant stimuli. Such effects would further distort the N2 components in the difference-waveforms. These arguments indicate that subtraction techniques are not helpful when comparing components that vary in latency, or when there is reason to suppose that completely different components are occurring at the same latency under different conditions (e.g. N2 and P3a). These difficulties are also present in other techniques such as principal components analysis where latency consistency is assumed. Because of these problems subtraction-techniques were not done in the subsequent experiments.

The N2-component elicited by all stimuli in the reading condition and the standard stimuli in the other two conditions are difficult to interpret. In the reading condition the 1050 Hz target evoked a late slow negative wave which was similar in latency and amplitude to the negative wave in the evoked potential to the standard stimulus. The 1500 Hz target, however, elicited an early small negativity which was maximally recorded frontally, as well as a later negative wave. Interestingly, the standard stimulus in the read condition evoked a central-maximum N2, while the 1050 Hz target elicited a frontal-maximum N2, but somewhat less frontal than the 1500 Hz target. These dif-

ferences in N2 scalp distributions suggest that in reading conditions, the standard, and perhaps those target stimuli close in frequency to it, evoke an N2 that is different from both the early frontal N2 elicited by the ignored 1500 Hz target and the late frontal N2 elicited by attended stimuli. One could postulate that this central-maximum N2 represents an exogenous component. The exogenous N2 elicited by attended standard stimuli in attend conditions may be combined with a small superimposed frontal negativity, as is suggested by its more frontal distribution (see section 4.3).

P3 and P3a components:

The P3 component results in this experiment were in general agreement with those previously reported (Donchin, 1979; Ritter et al., 1979; Duncan-Johnson and Donchin, 1982). The well-established increase in P3 latency and decrease in P3 amplitude with more difficult target-discriminations were clearly demonstrated. The latency delay has been related to the duration of stimulus evaluation (Duncan-Johnson and Donchin, 1982). The reduction in amplitude could have been partially due to averaging individual P3s which may have varied in timing (jitter) across trials. However, using compensation procedures, Ruchkin and Sutton (1978a; 1978b) have demonstrated that reduction in P3 amplitude cannot all be ascribed to jitter effects and have therefore postulated that some reduction in amplitude may be due to equivocation in target detection.

The 1500 Hz target in the reading condition elicited

an early positivity which was maximally recorded centrally and had a small amplitude (on average 1.0 uV at Cz). This appears to be the P3a component described by Squires et al. (1975) and Snyder and Hillyard (1976) in response to unattended deviant stimuli. The P3a component was not observed in the response to the 1050 Hz targets. The small amplitude of the P3a component may be explained by the fact that our subjects read an interesting novel for an extended and uninterrupted period of time. This may have made the targets less intrusive.

SW component:

The SW component was negative frontally and positive parietally. It was not significantly altered by differences in target-discriminability, but accurately distinguished both the 1500 Hz and the 1050 Hz targets from the standard stimuli. This finding replicates the results of Naatanen et al. (1980) and Fitzgerald and Picton (in press). The SW component therefore appears to be selectively elicited by target stimuli even in conditions where the target stimulus is very similar to the standard. Rohrbaugh et al. (1978) did find larger SW amplitudes for more difficult targets, but they used much slower rates of stimulus presentation. Our shorter inter-stimulus intervals may have attenuated any effects of target-discriminability on SW amplitude.

There were no significant differences between conditions A and B for the N2 and P3 components. The motor

response (button press) in condition B thus did not seem to have any significant effect on the evoked responses. The physical effort required for the motor response was small and the attendant motor potentials were probably of very low amplitude (Kutas and Donchin, 1974). On the strength of this result button press responses rather than counting tasks were used in subsequent experiments. The responses at C3 and C4 were mainly recorded to assess the possible influence of asymmetrical motor potentials. They were not analyzed in the subsequent experiments.

4.2. Experiment II

This experiment was designed to replicate and extend the findings obtained in the first experiment. Detected and missed targets were separately averaged. Four different targets were used to determine whether the findings in the first experiment were present over a continuum of increasing discrimination-difficulty.

N1 component:

The 1500 Hz target elicited a significantly larger N1 component than the standard stimulus. As in experiment I the amplitude of the N1 component was smaller for target stimuli closer in frequency to the more probable standard stimulus. However, this effect did not reach a significance level of $p < 0.01$. This may stem from the fact that there were target stimuli of intermediate frequencies interposed

between the target closest in frequency to the standard and the target furthest away, thereby decreasing the frequency specific recovery effects for the extreme frequency targets.

N2 component:

The N2 component had a longer peak latency and a larger amplitude with increasing difficulty of target-discrimination. There were no discontinuities or saturations of these effects noted over the range of targets evaluated. The N2 component was again maximum at the anterior scalp regions, and in fact was not found to alter in amplitude as a function of target-discriminability at the parietal electrode. The lack of a discrimination-difficulty effect for the N2 component at the parietal electrode argues strongly against the hypothesis that the earlier and larger P3 component, elicited by the easy target, overlaps the N2 component to cause a small early N2. In such a case, the parietal electrode, where P3 has maximal influence on the recorded response, should have manifested the largest, rather than the smallest, N2 differences between easy and difficult targets. As in experiment I the negativity elicited by the standard stimuli was late and small. The N2 elicited by the false alarms (incorrectly detected standard stimuli), appeared to be similar to the N2 elicited by the detected 1025 Hz target (although there were insufficient averages for a valid analysis). The frontal dominant N2 does not appear to be elicited solely as a function of

stimulus deviance, but rather occurs when any stimulus has been judged a target. Squires, Hillyard and Lindsay (1973) using an auditory threshold detection task found similar trends for the P3 component which was present for the evoked potentials during false alarms.

P3 component:

As in experiment I the P3 was significantly smaller in amplitude and later in latency as a function of increasing discrimination difficulty. Interestingly, the more difficult targets elicited a more parietal P3 component, as was also the case for experiment I. This change in scalp distribution may be a result of a superimposed posterior slow wave. Ruchkin, Sutton, Kietzman and Silver (1980) describe a positive slow wave which overlaps the P3 component at posterior scalp regions. Using a principal components analysis they found the slow wave to be larger when stimulus detection was more difficult and reaction times longer. They suggested that the slow wave could reflect the subject bringing "further processing efforts to bear in deciding whether a particular event has occurred". The peak measures for the frontal negative and parietal positive SW components in experiment I did not, however, display any significant effect of target-discrimination difficulty. It would appear that the parietal slow wave overlapping the P3 component, described by Ruchkin et al. (1980) was not identified by our SW measurements.

4.3. Experiment III

This experiment was designed to evaluate the effects of both the discriminability and the probability of the targets.

N2 component:

The N2 component in this experiment displayed consistent variations with manipulations of both discriminability and probability. As in the previous two experiments a difficult target-discrimination elicited a large and late N2 component. In this experiment it did so regardless of the probability of the target stimulus. It should be noted that although P3 amplitude was larger to the more improbable difficult target, the N2 was of comparable amplitude to that elicited by the probable difficult target. It would therefore appear that the large N2 to a difficult target is not the result of a small overlapping P3 component. The N2 remains large when the difficult target becomes very improbable and the P3 it elicits quite large.

The easy target (1800 Hz) elicited a large N2 component only when the target was very improbable. This large N2 to an easy (deviant) target agrees with the results of Ford et al. (1976), Naatanen et al. (1980) and Naatanen et al. (1982). The key difference which caused a large and early N2 component to be elicited in this experiment and not the previous two experiments was most likely the more improbable nature of the easy target stimulus (1.5% in this experiment

vs 10% and 5% in the previous experiments).

The N2 component elicited by targets in the reading conditions (C and D) appeared to be influenced by both target discriminability and probability. The target which elicited the largest N2 component was very improbable and highly removed in frequency from the standard stimulus. The N2 elicited by the standard stimulus in both conditions C and D were recorded maximally from the vertex, while target responses displayed a frontal maximum N2 component. As in experiment I, the attended standard stimulus appears to elicit both an exogenous N2 and a superimposed negativity, which causes it to have maximum amplitude at Fz. Considering scalp distribution, it would appear that due to the improbability and/or deviance of the target stimuli, an additional frontal negativity may be elicited in both attend and read conditions.

P3 and P3a components:

The P3 component was again smaller in amplitude and later in peak latency to the more difficult targets. The P3 amplitude was also increased when the eliciting target was more improbable (Squires, Wickens, Squires and Donchin, 1976; Fitzgerald and Picton, 1981). This effect was present regardless of alterations in target discriminability. Unlike the N2, the P3 was affected by probability for both easy and difficult targets,

The P3a components recorded in the reading conditions were influenced in a similar manner to the N2 component,

being best elicited by the very improbable highly deviant target. These results are in agreement with those of Naatanen et al. (1982). As in experiment I there was little, if any, P3a activity recorded to those targets closest in frequency to the standard. Even the P3a evoked by the deviant target was small in amplitude. Again, this was probably related to the subjects' having an extended and uninterrupted period of time to read.

General Discussion:

The increase in the amplitude of the N2 component to difficult target-discriminations is the most controversial point in the data and we shall attempt to explain this result first. We will then make several hypotheses about the various event-related potential components and the psychological processes of target-discrimination.

Recently, Naatanen et al. (1982) have proposed that there are two late negativities elicited by improbable deviant stimuli occurring in trains of otherwise homogeneous stimuli. They describe "N2a" as a modality specific component elicited by stimuli which deviate from or "mismatch" a standard. The greater the mismatch the larger the N2a component. In an auditory paradigm this component has a frontocentral scalp distribution with a clear central maximum. The N2a also appears to be probability dependent,

becoming greater in amplitude the more improbable the deviant stimulus (Naatanen et al., 1982; Naatanen, Sams, Jarvilehto, and Soininen, in press). Naatanen et al. (1982) have postulated that the N2a "may be considered an exogenous response, reflecting a discriminative process which responds in automatic fashion to environmental change, and which may be equivalent to the neuronal-mismatch process of orienting theory, but which does not itself imply detection of change". The N2 recorded in our experiments does not, on several important points, fit the description of the N2a. The negativity recorded here is largest to those target stimuli which are least deviant from the standard, the opposite from what would be hypothesized for N2a. The negativity we record has a much later latency range than any of the N2a data shown by Naatanen et al. (1980) or Naatanen et al. (1982). Furthermore, Naatanen et al. (1982) describe the scalp distribution of the N2a as modality specific and thus maximum in the central regions for auditory stimuli (cf. Simson, Vaughan and Ritter. 1976, 1977 a,b). Our N2 has maximum amplitude in the frontal regions. Finally, we found that the N2 elicited by difficult targets was not significantly altered by changing the probability of the target stimulus from 13.5% to 1.5%.

Naatanen et al. (1982) describe a second negativity labelled N2b, as part of an endogenous P2b-N2b-P3a complex. This negativity has a sharper peak morphology than the N2a and is frontal maximum. They have postulated that this N2b

reflects the detection of deviant stimuli, based on mismatch information provided by the N2a process. The N2b can occur either when attention is actively directed to the stimuli or when attention is passively drawn to the stimulus. Thus, N2b, not unlike the N2a, appears to be elicited best by very deviant and improbable stimuli. The large frontal early negativity that we recorded in experiment III in response to the very deviant (1800 Hz) and improbable (1.5%) target appears to fit the general description of an N2b component.

Renault and Lesevre (1978, 1979) originated the terms Na and Nb. They described a visually evoked modality specific negativity (Na) which is followed by a sharp negative peak (Nb). They postulated that the Na component reflects perceptual processing and the Nb component an orienting reaction. Ritter et al. (1979) describe an N2 component which they believe reflects a target discrimination-detection process (as opposed to automatic mismatching), but they specify that this N2 is modality specific. More recently, Ritter, Simson and Vaughan (in preparation) using a semantic discrimination task observed an early negativity (N_A) as well as a later N2 component. They hypothesize that the N_A reflects "pattern recognition" and the N2 component reflects subsequent "discrimination". Harter and Guido (1980) describe several task-dependent negativities which they believe reflect sequential stages of visual discrimination.

The large delayed negativity elicited by difficult

targets does not easily fit into any of the existing categories of N2 components as described above. Its scalp distribution makes it most similar to the N2b described by Naatanen et al. (1982). We therefore suggest that the frontal N2 occurring with difficult target discriminations can be classified, like the frontal N2 to detected easy targets, as an N2b component.

Naatanen et al. (1982) suggested that the N2b component reflects "detection" of environmental change based upon a previous mismatch process (N2a). They relate this detection process directly to stimulus deviance, such that the more deviant the stimulus the larger the N2b component. We suggest that, although the N2b is closely related to a preceding mismatch process, deviance is not always its determining factor. We propose that the N2b component reflects the allocation of effort to the evaluation of those stimuli that the initial mismatch process determines as possible targets. Once a stimulus has been found to mismatch a template, it is then evaluated in order to confirm or disconfirm its classification as a target, and subsequent to that its classification as a particular type of target. Because the negativity is frontally located, it possibly represents the activity of a frontally mediated effort allocating process rather than the activity of the perceptual processes to which effort is allocated. This distinction will, however, require further support from experiments in different modalities.

We hypothesize that the allocation of effort to stimulus evaluation has three main determinants: (1) a threshold for elicitation; (2) an operational level; and (3) a decision-criterion. These parameters of the allocation process are directly influenced by the task demands placed upon the subject. When attention is directed to the task of stimulus discrimination, stimuli are more easily able to invoke this allocation process (low threshold), and once invoked, the allocation process functions at a high operational level. The criterion whereby a response is generated, and allocation of effort terminated, depends upon the type of stimuli that the subject expects to perceive and the importance attributed to their detection. When attention is not directed toward stimulus discrimination, as in the reading conditions, the ability of stimuli to invoke the process is diminished (higher threshold), the operational level of the process is lower once it is invoked, and the criterion for response and/or termination of the process is much lower. Only highly improbable deviant stimuli will usually succeed in invoking the allocation process to a significant extent and the effort is quickly spent. A small and early N2b results. For difficult target-discriminations in attend conditions, the greater is the allocation of processing effort and the longer such allocation can be sustained. A large and late frontal N2b component is recorded. For an easy target-discrimination less allocation is necessary and a decision is reached in a shorter length

of time. This is reflected in a small and early N2b component.

The effects of probability are more complex. The N2b is larger for the more improbable easy target, but is equal for both probable and improbable difficult targets. There are two possible explanations for this result. First, the allocation process may be probability-sensitive but when the discrimination is sufficiently difficult to tax available resources the process may cease to be determined by probability. The second possibility is that the allocation process is not probability-sensitive. The larger N2b component elicited by improbable easy targets may occur because of an underlying N2a component. The N2a component reflects a probability-sensitive mismatch process and is larger in amplitude the more improbable the eliciting target, (cf. Naatanen et al., in press). The N2b component to an improbable easy target stimulus peaks quite early, and overlaps with the large N2a component resulting in an apparent enhancement of the N2b. When the easy target is probable there is still an overlapping of the N2a and the N2b components but the N2a is smaller and adds less to the N2b amplitude. For a difficult target the N2b is delayed beyond the N2a component. This results in the lack of any change with the probability of the difficult target. Generally, the overlapping of these negativities in this auditory paradigm is probably responsible for the fact that we fail to record a central maximum N2a component to target

stimuli. It is difficult to choose between these possibilities, although having the N2b insensitive to probability would be more parsimonious.

Our concept of N2b differs somewhat from that of Naatanen et al. (1982). They proposed that the N2b is a "sharp" frontal negative wave that occurs, as part of a P2b-N2b-P3a complex, when a stimulus is "salient". The salience of a stimulus is related to "its probability, magnitude of deviance and direction of attention". In our concept the N2b is a relatively independent process that is much more under the control of attention than either the probability or deviance of the stimulus. The duration and the amplitude of the N2b are determined by the attentional strategy. The N2b can be long and large if the subject considers worthwhile the allocating of much effort for prolonged durations to evaluating possible signals.

The model of stimulus discrimination we propose consists of three cascading stages (cf. McClelland, 1979). The first stage involves the automatic process of mismatch detection. Regardless of the attentional state, incoming stimuli are compared to an existing template. The greater the deviance of the stimulus from the template the larger the N1-N2a sequence of negativities. The intervening positivity (P2) does not appear to follow the same pattern of response as the surrounding negativities. It is possible the P2 represents an independent process. It is also possible that the N2b negativity overlaps the P2 component and

thus masks its responsiveness to stimulus deviance. If the mismatch does not exceed the threshold for activating the second stage of processing nothing further occurs and a small N1-P2-N2a complex is recorded.

If the mismatch exceeds threshold level the stimulus information is further evaluated in a controlled processing stage. This stage manifests itself in the frontal N2b wave. As we previously discussed the N2b is perhaps more related to the controlling rather than the controlled process. It perhaps indicates the amount of effort allocated to the verification of whether a stimulus is a target or not. Controlled processing continues until a final decision is reached about the stimulus. At that time a motor response may be initiated and higher order control processes activated.

The final stage in stimulus discrimination consists of higher order control processes. These are activated by the output of the second stage and feedback upon it to update the various parameters involved in the allocation of effort to stimulus-evaluation. The higher order control mechanisms can adjust the threshold for access to the second stage of processing, the operational level of that processing, and decision-criterion to be reached by that processing. We postulate that the amount and type of updating occurring in this final stage is indexed by the endogenous components, P3a, P3 and parietal slow wave, that follow the N2b. Generally, the more endogenous activity present after N2b

the more extensive is the updating. For example, when the output of the controlled processing stage is weak, as in the case of evaluating a deviant improbable stimulus in a read condition, the resultant updating, manifest in the P3a, is not extensive. When the output of the controlled processing is strong, as would occur after the evaluation of attended targets, the resultant updating would be extensive. This updating would be reflected by the P3 component (Donchin, 1979) and the parietal slow wave (Ruchkin, et al., 1980). The amount of updating would vary with the improbability of target occurrence (Duncan-Johnson and Donchin, 1977; Campbell, Courchesne, Picton and Squires, 1979) and the certainty with which it is discriminated (Ruchkin and Sutton, 1978b; Johnson and Donchin, 1978).

A key characteristic of the N2b component is its frontal maximum scalp distribution. This fact allows us to assess the controlled processing of stimuli that are not finally judged to be targets. In attend conditions a small percentage of standard stimuli are responded to as targets. This fact suggests that some of the standards are mismatched at the level of the N1-N2a process. The degree of mismatch would most likely be very small. Due to the small degree of mismatch the evaluation of this stimulus would be difficult, thus involving a large and lengthy allocation of effort much the same as for the evaluation of a difficult target. These standards would display large late N2b components. A small percentage (less than 1% in experiment II) of these stand-

ards are evaluated and subsequently classified as targets (false alarms). Those standards that are evaluated and classified as standards (correct rejections) will also display large late N2b components. The averaging together of all standards, correctly rejected at the level of the N1-N2a mismatch process and at the level of the controlled processing (N2b), results in the recording of only a small frontocentral negativity. The fact that the standard stimuli in reading conditions have a clearly central N2 suggests that few, if any, standards had gained access to the controlled processing stage. This would be a result of the higher threshold for eliciting controlled processing in reading conditions.

We have suggested that the N2b is a metric of the allocation of effort to stimulus-evaluation. The more effort required the longer and larger the N2b component. The studies of Ford et al. (1976) and Naatanen et al. (1980), however, failed to record a late large negativity to what appeared to be difficult target-discriminations. There are several possible explanations for this lack of an N2b difficulty effect in these studies. They both show only a small N2b-latency change when comparing easy and difficult target-discriminations (Table 5). This suggests that the subjects may have found the task easy and thus allocated less controlled processing to the detected targets. In this regard, Naatanen et al. (1980) used stimuli of a relatively long duration (150 msec) which could have decreased the

difficulty of target detection. These studies also used relatively improbable target stimuli which may have caused an increase in the N2a negativity following the easy target-discriminations, thereby decreasing the differences in N2b amplitude between easy and difficult targets. Finally, Naatanen et al. (1980) did not separately average detected and missed targets. More difficult than easy targets would have been missed and the N2 component to the difficult target attenuated.

The results of our previous study (Fitzgerald and Picton, in press) appear to be inconsistent with the model we have developed here. In this study we obtained small N2-latency differences between the easy and difficult target discriminations, and yet recorded larger N2 amplitudes to the difficult target discriminations. Our model would predict that the N2b elicited by difficult discriminations should be prolonged. A possible explanation for this finding may be found in the accuracy of performance (Table 5). The very low rates of missed targets in this study suggests that the subjects were highly engaged in the task of target-detection, and generated an increased N2 amplitude even at short latencies.

CONCLUSION

The model of stimulus evaluation that we have proposed, based upon the component structure of the event-related potentials, consists of three overlapping stages. The stage of automatic processing involves a comparison of incoming stimuli to a template and is reflected at the scalp by the N1-N2a complex. The stage of controlled processing carries out the evaluation of stimuli that do not exactly match the template. This process is reflected at the scalp by the N2b component. This stage is loosely determined by the improbability and deviance of the target, since it is only accessed if the mismatch process exceeds a threshold. The amount and duration of the processing is determined by attentional strategy. The final stage in the sequence is composed of the higher order control processes which function to modify or update the parameters of the controlled processing stage. This updating is reflected at the scalp by the P3a, P3 and parietal slow wave. The amount and type of updating depends on the improbability of the signal, the certainty of its detection, and the attentional strategy.

REFERENCES

- Butler, R.A. (1968). Effects of changes in stimulus frequency and intensity on habituation of the human vertex potential. *The Journal of the Acoustical Society of America*, 44, 945-950.
- Campbell, K., Courchesne, E., Picton, T.W. and Squires, K.C. (1979). Evoked potential correlates of human information processing. *Biological Psychology*, 8, 45-68.
- Campbell, K., Marois, R. and Arcand, L. (in press). Ethanol and the event-related potentials: Effects of rate of stimulus presentation and task difficulty. In: Cohen, J., Karrer, R. and Teuting, P. (Eds.). *Proceedings of the Sixth International Conference on Event-related Slow Potentials of the Brain*.
- Davis, H., Mast, T., Yoshie, N. and Zerlin, S. (1966). The slow response of the human cortex to auditory stimuli: recovery processes. *Electroencephalography and Clinical Neurophysiology*, 21, 105-113.
- Donchin, E. (1979). Event-related brain potentials: A tool in the study of human information processing. In: Begleiter, H. (Ed.), *Evoked Brain Potentials and Behavior*. Plenum Press: New York.

Duncan-Johnson, C.C. and Donchin, E. (1977). On quantifying surprise, the variation of event-related potentials with subjective probability. *Psychophysiology*, 14, 456-467.

Duncan-Johnson, C.C. and Donchin, E. (1982). The P300 component of the event-related brain potential as an index of information processing. *Biological psychology*, 14, 1-52.

Fitzgerald, P.G. and Picton, T.W. (1981). Temporal and sequential probability in evoked potential studies. *Canadian Journal of Psychology*, 35, 188-200.

Fitzgerald, P.G. and Picton, T.W. (in press). The effects of probability and discriminability on the evoked potentials to unpredictable signals. In: Cohen, J., Karrer, R. and Teuting, P. (Eds.). *Proceedings of the Sixth International Conference on the Event-related Slow Potentials of the Brain*.

Ford, J.M., Roth, W.T. and Kopell, B.S. (1976). Auditory evoked potentials to unpredictable shifts in pitch. *Psychophysiology*, 13, 32-39.

Goodin, D.S., Squires, K.C., Henderson, B.H. and Starr, A.

(1978). An early event-related cortical potential.

Psychophysiology, 15, 360-365.

Goodin, D.S., Squires, K.C. and Starr, A. (unpublished manu-

script, 1979). Variations in the early and late endogenous

evoked potential components with task difficulty.

Harter, M.R. and Guido, W. (1980). Attention to pattern

orientation: Negative cortical potentials, reaction time,

and the selection process. Electroencephalography and

Clinical Neurophysiology, 49, 461-475.

Johnson, R. Jr., and Donchin, E. (1978). On how P300 amplitude

varies with the utility of the eliciting stimuli. Electro-

encephalography and Clinical Neurophysiology, 44, 424-437.

Kutas, M. and Donchin, E. (1974). The effect of handedness,

the responding hand and response force on the contralateral

dominance of the readiness potential. Science, 186, 545-548.

McClelland, J. (1979). On the time relations of mental processes:

A framework for analyzing processes in cascade. Psychological

Review, 86, 287-330.

Naatanen, R., Hukkanen, S. and Jarvilehto, T. (1980). Magnitude of stimulus deviance and brain potentials. In: Kornhuber, H.H. and Deeke, L. (Eds.). Motivation, Motor and Sensory Processes of the Brain: Electrical Potentials, Behavior and Clinical Use. Progress in Brain Research Vol. 54. Elsevier/North-Holland: Amsterdam.

Naatanen, R., Sams, M., Jarvilehto, T. and Soininen, K. (in press). Probability of deviant stimulus and event-related brain potentials. In: Sinz, R. and Rosenzweig, M. Eds.). Psychophysiology. Gustav Fischer Verlag: Berlin, DDR.

Naatanen, R., Simson, M. and Loveless, N.E. (1982). Stimulus deviance and evoked potentials. Biological Psychology, 14, 53-98.

Nelson, D.A. and Lassman, F.M. (1968). Effects of inter-signal interval on the human auditory evoked response. The Journal of the Acoustical Society of America, 44, 1529-1532.

Picton, T.W., Hillyard, S.A. and Galambos, R. (1976). Habituation and attention in the Auditory system. In: Keidal, W.D., Neff, W.D. (Eds.). Auditory System: Clinical and Special topics. Handbook of Sensory Physiology, Vol 3. Springer-Verlag: New York.

Picton, T.W., Woods, D.L. and Proulx, G.B. (1978a). Human auditory sustained potentials. I. The nature of the response. *Electroencephalography and Clinical Neurophysiology*, 45, 186-197.

Picton, T.W., Woods, D.L. and Proulx, G.B. (1978b). Human auditory sustained potentials. II. Stimulus relationships. *Electroencephalography and Clinical Neurophysiology*, 45, 198-210.

Renault, B. and Lesevre, N. (1978). Topographical study of the emitted potential obtained after omission of an expected visual stimulus. In: Otto, D. (Ed.). *Multidisciplinary Perspectives in Event-related Brain Potential Research*. U.S. Government Printing Office: Washington, D.C.

Renault, B and Lesevre, N. (1979). A trial-by-trial study of the visual omission response in reaction time situations. In: Lehmann, D. and Callaway, E. (Eds.). *Human Evoked Potentials*. Plenum Press: New York.

Ritter, W., Simson, M. and Vaughan, H.G. (in preparation). Event-related potential correlates of two stages of information processing in physical and semantic discrimination tasks.

Ritter, W., Simson, R., and Vaughan, H.G. and Friedman, D.

(1979). A brain event related to the making of a sensory discrimination, *Science*, 203, 1358-1361.

Rohrbaugh, J.W., Syndulko, K. and Lindsley, D.B. (1978).

Cortical slow negative waves following non-paired stimuli: Effects of task factors. *Electroencephalography and Clinical Neurophysiology*, 45, 551-567.

Ruchkin, D.S., McCalley, M.G and Glaser, E.M. (1977). Event related potentials and time estimation. *Psychophysiology*, 14, 451-455.

Ruchkin, D.S. and Sutton, S. (1978a). Emitted P300 potentials and temporal uncertainty. *Electroencephalography and Clinical Neurophysiology*, 45, 268-277.

Ruchkin, D.S. and Sutton, S. (1978b). Equivocation and P300 amplitude. In: Otto, D.A., (Ed.). *Multidisciplinary Perspectives in Event-related Brain Potential Research*. U.S. Government Printing Office: Washington, D.C.

Ruchkin, D.S., Sutton, S., Kietzman, M.L. and Silver, K. (1980). Slow wave and P300 in signal detection. *Electroencephalography and Clinical Neurophysiology*, 50, 35-47.

Simson, R., Vaughan, H.G. and Ritter, W. (1976). The scalp topography of potentials associated with missing visual and auditory stimuli. *Electroencephalography and Clinical Neurophysiology*, 40, 33-42.

Simson, R., Vaughan, H.G. and Ritter, W. (1977a). The scalp topography of potentials in auditory and visual discrimination tasks. *Electroencephalography and Clinical Neurophysiology*, 42, 528-535.

Simson, R., Vaughan, H.G. and Ritter, W. (1977b). The scalp topography of potentials in auditory and visual Go/NoGo tasks. *Electroencephalography and Clinical Neurophysiology*, 43, 864-875.

Snyder, E. and Hillyard, S.A. (1976). Long-latency evoked potentials to irrelevant, deviant stimuli. *Behavioral Biology*, 16, 319-331.

Squires, K.C., Hillyard, S.A. and Lindsay, P.H. (1973). Vertex potentials evoked during auditory signal detection: Relation to decision criteria. *Perception and Psychophysics*, 14, 265-272.

Squires, N.K., Squires, K.C. and Hillyard, S.A. (1975). Two varieties of long-latency positive waves evoked by unpredictable auditory stimuli in man. *Electroencephalography and Clinical Neurophysiology*, 38, 387-401.

Squires, K.C., Wickens, C., Squires, N.K. and Donchin, E. (1976).

The effect of stimulus sequence on the waveform of the cortical event-related potential. *Science*, 193, 1142-1146.

Verleger, R., Gasser, T. and Mocks, J. (1982). Correction of

EOG artifacts in event-related potentials of the EEG:

Aspects of reliability and Validity. *Psychophysiology*,

19, 472-480.

Woody, C.D. (1967). Characterization of an adaptive filter

for the analysis of variable latency neuroelectric signals.

Medical and Biological Engineering, 5, 539-553.

7

TABLE 1

Experiment I. Mean amplitudes in uv and latencies in msec for N=12.

	Fz		Cz		Pz		C3		C4		Cz	
	N2	P3	N2	P3	N2	P3	N2	P3	N2	P3	N2	P3 (latency)
Condition A												
1050 Hz target	-4.0	0.6	-3.1	4.5	-1.0	7.2	-3.0	3.0	-2.6	3.4	287	450
1500 Hz target	-2.0	5.7	-0.6	10.2	1.0	11.5	-0.9	7.3	-0.7	7.5	236	336
1000 Hz Standard	-2.8		-2.8		-1.1		-1.6		-1.2		305	
Condition B												
1050 Hz target	-4.1	0.2	-4.0	2.6	-0.8	8.5	-2.8	1.9	-2.1	3.4	301	436
1500 Hz target	-2.1	6.2	-1.3	8.8	1.2	12.5	-0.7	6.8	-1.1	8.1	231	337
1000 Hz Standard	-3.0		-2.5		-0.6		-1.2		-1.0		317	
Condition C												
1050 Hz target	-3.2		-3.0		-2.0		-2.5		-1.8		256	
1500 Hz target	-1.9	0.2	-1.3	1.0	-1.3	0.9	-1.6	0.4	-1.0	0.6	215	262
1000 Hz standard	-2.1		-2.3		-1.3		-1.6		-1.0		290	

TABLE 2

Experiment II. Mean amplitudes in μV and latencies in msec for N=10.

	Fz		Cz		Pz		Cz	
	N2	P3	N2	P3	N2	P3	N2	P3
							(latency)	
1025 Hz target	-6.8	-1.2	-6.5	1.1	-3.0	7.6	315	474
1050 Hz target	-5.4	-0.5	-5.0	2.5	-1.2	6.8	282	401
1100 Hz target	-4.2	0.8	-4.2	3.8	-1.6	8.4	250	371
1500 Hz target	-3.5	4.3	-3.2	8.8	-1.2	12.2	207	312

TABLE 3

Experiment III. Mean amplitudes in μV and latencies in msec for N=8.

(ATTEND)	Fz		Cz		Pz		Cz	
	N2	P3	N2	P3	N2	P3	N2	P3
Condition A								
1050 Hz target (1.5%)	-4.8	2.9	-2.4	9.8	0.4	10.5	259	376
1200 Hz target (4.5%)	-2.4	2.0	-1.1	7.8	0.8	9.5	221	371
1800 Hz target (13.5%)	-0.7	4.9	0.3	9.2	1.5	9.1	198	301
1000 Hz Standard (80.5%)	-2.1		-1.2		-0.1		311	
Condition B								
1050 Hz target (13.5%)	-3.8	0.1	-2.5	4.2	-0.2	5.5	252	377
1200 Hz target (4.5%)	-2.6	4.1	-1.8	8.5	0.3	9.6	208	333
1800 Hz target (1.5%)	-3.1	10.2	-2.8	15.2	-1.9	13.4	185	298
1000 Hz standard (80.5%)	-2.2		-1.2		0.0		304	

(latency)

TABLE 4

Experiment III. Mean amplitudes in μV and latencies in msec for N=8.

(READ)	Fz		Cz		Pz		Cz	
	N2	P3a	N2	P3a	N2	P3a	N2 (latency)	P3a
Condition C								
1050 Hz target (1.5%)	-2.2	0.0	-1.6	0.9	-0.5	1.2	183	252
1200 Hz Target (4.5%)	0.2	0.9	0.3	1.6	0.7	1.4	185	226
1800 Hz target (13.5%)	-0.1	0.3	0.6	0.5	0.1	0.6	201	253
1000 Hz standard (80.5%)	-1.1		-1.6		-0.6		298	
Condition D								
1050 Hz target (13.5%)	-0.2	0.2	0.4	0.7	0.5	0.7	188	233
1200 Hz target (4.5%)	-1.1	-0.4	-1.0	0.2	-1.4	-0.2	183	227
1800 Hz target (1.5%)	-1.9	2.2	-1.0	3.2	-1.0	1.7	183	245
1000 Hz standard (80.5%)	-1.0		-1.1		-0.5		284	

TABLE 5

	N	STIMULI Dur. msec	ISI sec	Target ¹ Prob. (%)	Frequency ² separations	N2 lat ³ diff. (D-E)	N2 amp. ⁴ result	RT ⁵ msec	% MISS ⁶
Ford et al. 1976	12	50	1.0-3.0	2-8	50 Hz 500 Hz	28 ms	-	461 380	11.0 4.0
Ritter et al. 1979	4	50	2.5	10	30 Hz 1000 Hz	41 ms	+	386 333	
Naatanen et al., 1980	6	150	0.84	5	44 Hz 500 Hz	18 ms	-		8.0
Naatanen et al., 1982	9	42	0.77	diff 2 easy 1	34 Hz 404 Hz	50 ms	0		10.9 0.0
Fitzgerald and Picton, 1983	10	55	0.5-2.0	20	100 Hz 1000 Hz	10 ms	+		3.0 1.2
Campbell et al., 1983	10	55	1.5	25	25 Hz 500 Hz	65 ms	+		8.1 0.7
Experiment I	12	55	1.1	10	50 Hz 500 Hz	61 ms	+	497 401	20.0 2.0
Experiment II	10	55	1.1	5	25 Hz 500 Hz	108 ms	+	531 357	70.5 1.8
Experiment III, Condition A	8	55	1.1	diff 1.5 easy 13.5	50 Hz 800 Hz	61 ms	+	490 337	16.0 0.9
Experiment III Condition B	8	55	1.1	diff 13.5 easy 1.5	50 Hz 800 Hz	67 ms	0	459 343	25.0 0.9

Explanatory notes for Table 5:

(1) Target Prob.: The sequential probability of the target stimulus. For each study all targets are of equal probability unless otherwise indicated.

(2) Frequency Separation: The difference in Hz between the standard stimulus and the difficult target or the easy target. If more than two targets are presented the easiest and most difficult are evaluated. The standard stimuli in all experiments had a frequency of 1000 Hz (except Ford et al. (1976) which used a 500 Hz target for half of the subjects).

(3) N2 lat Diff. (D-E): The mean N2 latency difference between the difficult (D) and easy (E) target stimuli.

(4) N2 amp. result: The reported result of N2 amplitude change as a function of target discriminability. The following notation is used to summarize the individual findings.

- + a trend for larger N2 amplitudes to difficult target discriminations.
- + + significantly larger N2 amplitudes to difficult target discriminations.
- 0 equal N2 amplitudes to easy and difficult target discriminations.
- - significantly larger N2 amplitudes to easy target discriminations.
- a trend for larger N2 amplitudes to easy target discriminations.

(5) RT: The mean reaction time in msec to difficult target discriminations and easy target discriminations.

(6) % Miss: The average percentage of missed difficult target stimuli and easy target stimuli. If only one percentage is listed this would represent the total percentage missed for all target stimuli.

Figure Legends:

Figure 1. Grand-mean target-evoked potentials for the 12 subjects, recorded from Fz, Cz, Pz, C3 and C4 electrodes in condition A (count) of experiment I. The downward pointing arrows indicate (left to right) the N2 and P3 components to the 1050 Hz (difficult) target. The upward pointing arrows indicate the N2 and P3 components to the 1500 Hz (easy) target. Negativity of the scalp electrodes relative to a linked-mastoid reference is represented by an upward deflection.

Figure 2. Grand-mean target-evoked potentials for the 12 subjects, recorded from Fz, Cz, Pz, C3 and C4 electrodes in condition B (respond) of experiment I. Corresponding reaction time histograms are shown at the lower right corner of the figure. The reaction time histogram was plotted using a bin size of 13.5 msec and a vertical scale which in percentage of responses is equal to the vertical scale in μV of the evoked potential (in this case 10%). Negativity of the scalp electrodes relative to a linked-mastoid reference is represented by an upward deflection.

Figure 3. Grand-mean target-evoked potentials for the 12 subjects, recorded from Fz, Cz, Pz, C3 and C4 electrodes in condition C (read) of experiment I. The arrow indicates the

central maximum P3a component. Negativity of the scalp electrodes relative to a linked-mastoid reference is represented by an upward deflection.

Figure 4. Target-evoked potentials from subject BB, recorded from Fz, Cz, Pz, C3 and C4 electrodes in condition A (count) of experiment I. The arrow indicates the N2 elicited by the 1500 Hz (easy) target which is larger in amplitude than that elicited by the 1050 Hz (difficult) target. Negativity of the scalp electrodes relative to a linked-mastoid reference is represented by an upward deflection.

Figure 5. Grand-mean target and standard-evoked potentials for the 10 subjects, recorded from Fz, Cz and Pz electrodes in experiment II. Corresponding reaction time histograms are shown at the right of figure. The reaction time histograms are plotted as in figure 2. Negativity of the scalp electrodes relative to a linked-mastoid reference is represented by an upward deflection.

Figure 6. Grand-mean 1025 Hz target and 1000 Hz standard evoked potentials for the 10 subjects, recorded at Fz, Cz and Pz electrodes in experiment II. The upper half of the figure shows the Hit and Miss 1025 Hz target-evoked potentials. The lower half of the figure shows the false alarms (F.A.) and correct rejected (C.R.) 1000 Hz standard-evoked potentials. The N2 component at Fz and the P3 component at

Pz of the 1000 Hz standard F.A. response are indicated by downward and upward pointing arrows respectively. The reaction time histograms are plotted as in figure 2. Negativity of the scalp electrodes relative to a linked-mastoid reference is represented by an upward deflection.

Figure 7. Grand-mean target-evoked potentials for the 8 subjects, recorded from Fz, Cz and Pz electrodes in the attend conditions of experiment III. The upper half of the figure shows the responses to the 1.5% target stimuli in condition A (1050 Hz) and condition B (1800 Hz). The lower half of the figure shows the responses to the 13.5% target stimuli in condition A (1800 Hz) and condition B (1050 Hz). The reaction time histograms are plotted as in figure 2. Negativity of the scalp electrodes relative to a linked-mastoid reference is represented by an upward deflection.

Figure 8. Grand-mean target-evoked potentials for the 8 subjects, recorded from Fz, Cz and Pz electrodes in the read conditions of experiment III. The upper half of the figure shows the responses to the 1.5% target stimuli in condition C (1050 Hz) and condition D (1800 Hz). The arrow indicates the central maximum P3a component elicited by the 1.5% 1800 Hz target. The lower half of the figure shows the responses to the 13.5% target stimuli in condition C (1800 Hz) and condition D (1050 Hz). Negativity of the scalp electrodes

relative to a linked-mastoid reference is represented by an upward deflection.

Figure 1

Figure 2

DIFFICULT TARGET —
EASY TARGET

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Appendix A. The effects of probability and
discriminability on the evoked
potentials to unpredictable
signals

THE EFFECTS OF PROBABILITY AND DISCRIMINABILITY ON
THE EVOKED POTENTIALS TO UNPREDICTABLE STIMULI *

Peter G. Fitzgerald and Terence W. Picton

The detection of unpredictable "target" stimuli in a train of "standard" stimuli has been associated with several distinct components of the human evoked potential (Ritter & Vaughan, 1969; Squires & Hillyard, 1975; Ford, Roth & Kopell, 1976; Goodin, Squires, Henderson & Starr, 1978). The amplitude of one of these components - the late positive component, "P3" or "P300" - is closely related to the improbability of the stimulus (Squires, Wickens, Squires & Donchin, 1977).

The occurrence of an unpredictable target may be described in terms of either "temporal probability" - the probability of a target within a given period of time -, or "sequential probability" - the probability of a target within a number of stimuli (Picton & Stuss, 1980)¹. Recent results (Fitzgerald & Picton, 1981) have suggested that temporal rather than sequential probability may be the major determining factor for P3 amplitude. These experiments used a relatively simple discrimination task. The present study was designed to determine whether the effect of temporal probability was independent of task difficulty. Would a

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more difficult target-standard discrimination require more attention to the standard stimuli and to the sequential probability of the target, thereby decreasing the effects of temporal probability?

Methods

Ten young adult subjects participated in the experiment. Their task was to keep a running mental count of the number of targets occurring in 7-minute trains of auditory stimuli. The sequential probability of the target was maintained constant at 0.2. Three different inter-stimulus intervals were used to give three temporal probabilities for the target stimulus: 500 ms - $1/2.5$ s; 1000 ms - $1/5$ s; 2000 ms - $1/10$ s. Two different degrees of difficulty in target-standard discriminations were used. In the "difficult" conditions the target stimuli were 1000 Hz tones and the standard stimuli were 1100 Hz tones. In the "easy" condition the frequency of the target remained at 1000 Hz and the standard frequency was changed to 2000 Hz. The tones had a total duration of 55 ms, rise and fall times of 5 ms each, and an intensity of 65 dB peak SPL (about 50 dB SL). They were presented through earphones to the right ear.

Electroencephalographic signals were recorded from Fz, Cz and Pz using a linked-mastoid reference. An electro-oculogram was recorded between the upper and lower orbital ridges of the left eye. These recordings were amplified

using a time constant of 8.2 s and a high frequency cut-off of 100 Hz. Averaging was performed on a TN1500 Signal Analyzer using 4 ms dwell times. Trials with excessive muscle or eye movement artifact were eliminated from the averaging process. Difference-waveforms were obtained by subtracting the average evoked potentials to the standard stimuli from those to the target stimuli. Peak components were identified in the following latency ranges: N1 (65 - 140 ms), P2 (130 - 230 ms), N2 (180 - 270 ms), P3 (250 - 400 ms) and SW (400 - 800 ms). The peaks were measured relative to the baseline at the beginning of the evoked potential tracing. The data were analyzed using repeated measures analyses of variance and results were considered significant at $p < 0.01$.

Results

The subjects reported the "difficult" conditions to be more demanding. The average error rate of 3.0% for the difficult conditions was significantly greater than the 1.2% for the easy conditions. There were no significant effects of temporal probability on these percentage error rates.

The N1 component increased in amplitude with increasing inter-stimulus interval for both target and standard stimuli. The N1 to the targets was larger than to the standard stimuli, this difference being greater in the easy conditions and at the shorter inter-stimulus intervals. These N1 effects can be clearly seen by examining the difference waveforms at the N1 latency period (100 ms). The P2

component also increased in amplitude with increasing inter-stimulus interval. There were no significant differences between the target and standard stimuli. However, the target P2 components were larger in the easy conditions than in the difficult.

The evoked potentials to the standard stimuli did not show any definite N2, P3 or slow-wave components. The N2 component in the target-evoked potential did not change significantly with increasing inter-stimulus interval. Its amplitude increased significantly, however, with increasing task difficulty, being on average 2.8 uV in the difficult conditions and 1.0 uV in the easy. The peak-latency in the difficult conditions was 237 ms and in the easy conditions was 227 ms but this difference did not reach significance. The analysis of the subtraction waveforms gave similar results. The P3 component in the target-evoked potential increased in amplitude with increasing inter-stimulus interval. It was larger in the easy than in the difficult conditions, but the temporal probability effect was roughly parallel between these conditions. The average P3 amplitude at Cz increased with inter-stimulus interval from 1.9 uV to 6.0 uV in the difficult conditions and from 4.6 uV to 8.6 uV in the easy conditions. The latency of the P3 component was unaffected by changing inter-stimulus intervals but was significantly larger for difficult (361 ms) as compared to the easy (332 ms) conditions. The slow-wave component of the target-evoked potential was recorded as a negativity at Fz and as a positivity at Pz. Neither showed any signific-

ant effect of either inter-stimulus interval or task difficulty.

Discussion

The increase in N1 and P2 amplitude with increasing interstimulus intervals can be explained by the prolonged refractory period of the auditory vertex potential (Davis, Mast, Yoshie & Zerlin, 1966). The larger amplitude of the N1 component in the target-evoked potential may be caused by the frequency-specificity of this refractory period (Butler, 1968) - the target tone more usually followed a stimulus of different frequency than the standard tone. The N1 to targets in the easy condition was larger than in the difficult condition because of the greater target-standard frequency separation. It is also possible that these effects may be due to the superimposition on the N1 of a "mismatch-negativity" (Naatanen et al., in press). The P2 component of the target-evoked potential showed similar frequency-specificity effects being larger in the easy conditions. The absence of any significant P2 differences between targets and standards was perhaps due to the overlapping N2 component in the target-evoked potential.

The target-evoked potential contained N2, P3 and slow-wave components that were not present in the standard-evoked potential. The N2 component of the target-evoked potential was unaffected by increasing the inter-stimulus interval but was significantly larger during the difficult conditions. In our previous experiment (Fitzgerald & Picton, 1981)

increasing the inter-stimulus interval over a wider range caused a significant increase in the N2 as measured in the difference-waveforms. The interpretation of the N2 wave is difficult because of the overlapping P2 -components. If the P2 shows similar frequency-specificity effects to those of the N1, the difference between the target and the standard P2 would be greater at the shorter inter-stimulus intervals. This might explain the increase in the N2 amplitude in the difference waveform with increasing inter-stimulus interval in our previous experiments - the overlapping P2 difference would be decreasing. The larger amplitude of the N2 for the difficult conditions persists out to the longer inter-stimulus intervals. This suggests that it is not all related to the smaller amplitude of the overlapping P2 in the difficult conditions but that there is also an underlying relationship of N2 amplitude to task difficulty. Goodin, Squires and Starr (unpublished data) have reported that the N2 increased significantly in latency and showed a small but not significant change in amplitude with increasing difficulty on an intensity-discrimination target-detection task. Naatanen, Hukkanen and Jarvilehto (1980) have reported different findings from our results with N2 being larger the more "deviant" the target from the standard tone. Our experiment did not combine both discriminations in the same stimulus block, and therefore there was quite probably a difference in effort between our conditions. Further experiments will be required to clarify the effects of task-difficulty on the N2 component.

The slow-wave component showed a significant target-standard difference. The lack of any significant effects of interstimulus interval differs from our previous experiment (Fitzgerald & Picton, 1981). This may be explained by the larger range of intervals (250 ms - 4 s) used in the previous study. The lack of any task-difficulty effect is somewhat different from the results of Rohrbaugh, Syndulko and Lindsley (1978). Their study, however, compared a difficult discrimination task to a simple counting task and used longer interstimulus intervals.

The P3-component showed a large effect of temporal probability in both the easy and difficult conditions. This reinforces the conclusions of our previous experiments that the temporal probability of the target is a major determinant of the P3 amplitude. The P3 amplitude was smaller and P3 latency longer for the more difficult discrimination. This is similar to previous reports (Goodin et al., unpublished data; Naatanen et al., 1980) and is possibly related to equivocation in the target detection (Ruchkin & Sutton, 1978). In answer to the question posed at the onset of these experiments, our results show that temporal probability is a major determinant of P3 amplitude regardless of the difficulty of target discrimination.

References

- Butler, R.A. Effect of changes in stimulus frequency and intensity on habituation of the human vertex potential. Journal of the Acoustical Society of America, 1968, 44, 945-950.
- Davis, H., Mast, T., Yoshie, N., & Zerlin, S. The slow response of the human cortex to auditory stimuli: recovery processes. Electroencephalography and Clinical Neurophysiology, 1966, 21, 105-113.
- Duncan-Johnson, C.C., & Donchin, E. On quantifying surprise: The variation of event-related potentials with subjective probability. Psychophysiology, 1977, 14, 456-467.
- Fitzgerald, P.G., & Picton, T.W. Temporal and sequential probability in evoked potential studies. Canadian Journal of Psychology, 1981, 35, 188-200.
- Ford, J.M., Roth, W.T., & Kopell, B.S. Auditory evoked potentials to unpredictable shifts in pitch. Psychophysiology, 1976, 13, 32-39.
- Goodin, D.S., Squires, K.C., Henderson, B.H., & Starr, A. An early event-related cortical potential. Psychophysiology, 1978, 15, 360-365.
- Goodin, D.S., Squires, K.C., & Starr, A. Variations in early and late endogenous evoked potential components with task difficulty. 1981, manuscript in preparation.
- Naatanen, R., Hukkanen, S., & Jarvilehto, T. Magnitude of stimulus deviance and brain potentials. In: H.H. Kornhuber & L. Deecke (Eds.), Progress in Brain Research, Vol. 54: Motivation, Motor and Sensory Processes of the Brain: Electrical Potentials, Behavior and Clinical Use. Amsterdam, Elsevier, 1980.
- Naatanen, R., Simpson, M., & Lovelless, N.E. Stimulus deviance and evoked potentials. Biological Psychology, in press.
- Picton, T.W., & Stuss, D. The component structure of the human event-related potentials. In H.H. Kornhuber & L. Deecke (Eds.), Progress in brain Research. Volume 54. Motivation, motor and sensory processes of the brain: Electrical potentials, behavior and clinical use. Amsterdam, Elsevier, 1980, pp 17-49.
- Ritter, W., & Vaughan, H.G. Average evoked responses in vigilance and discrimination: a reassessment. Science, 1969, 164, 326-328.

- Rohrbaugh, J.W., Syndulko, K., & Lindsley, D.B. Cortical slow negative waves following non-paired stimuli: Effects of task factors. Electroencephalography and Clinical Neurophysiology, 1978, 45, 551-567.
- Ruchkin, D.S., & Sutton, S. Equivocation and P300 amplitude. In D. Otto (Ed.), Multidisciplinary Perspectives in Event-related Brain Potential Research. Washington: US Environmental, 1978, Protection Agency pp 175-177
- Squires, N.K., Squires, K.C., & Hillyard, S.A. Two varieties of long-latency positive waves evoked by unpredictable auditory stimuli in man. Electroencephalography and Clinical Neurophysiology, 1975, 38, 387-401.
- Squires, K.C., Wickens, C., Squires, N.K., & Donchin, E. The effect of stimulus sequence on the waveform of the cortical event-related potential. Science, 1976, 193, 1142-1146.

Footnote:

1

Many different terms have been used to describe the probability of a target. Our choice of "temporal" and "sequential" derives from the paper of Ford et al. (1976). Other authors have used "event probability" for what we describe as sequential probability, but we feel this is ambiguous. Further refinement can be obtained by using the additional terms "local" and "global". The global sequential probability of a target may be 0.5 but in a particular portion of the experiment containing (by design or chance) many targets the local sequential probability may be much higher than 0.5.

Figure Legends:

Figure 1. Vertex grand average waveforms for the ten subjects. Evoked potentials to the targets (T) are shown in the top line and to the standards (S) in the middle line. The bottom line shows the difference (T-S) waveforms. Negativity of the scalp electrode relative to a linked-mastoid reference is represented by an upward deflection.

Figure 2. Grand average difference waveforms (T-S) for the ten subjects at all conditions and scalp electrode locations. Negativity of the scalp electrode relative to a linked-mastoid reference is represented by an upward deflection.