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An electrophysiological and psychophysical investigation of spatial contrast discrimination in human vision

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AN ELECTROPHYSIOLOGICAL AND PSYCHOPHYSICAL INVESTIGATION OF SPATIAL CONTRAST DISCRIMINATION IN HUMAN VISION

by

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Abstract

AN ELECTROPHYSIOLOGICAL AND PSYCHOPHYSICAL INVESTIGATION OF SPATIAL CONTRAST DISCRIMINATION IN HUMAN VISION

by

Gloria L. Kass

Advisor: Professor Ivan Bodis-Wollner, M.D.

Discrimination of intensity differences has been studied in the past by both electrophysiological and psychophysical methods. It has been shown that an ERP measure, the P300 (P3) varies as a function of the difference in intensity between two suprathreshold stimuli.

This study investigated: (1) The minimum contrast difference between two grating patterns required to elicit a P3. (2) The change of P3 latency and amplitude as a function of the contrast difference. (3) The psychophysical contrast discrimination threshold for the same stimuli. The major aim was to correlate the electrophysiological and the psychophysical indices of contrast discrimination.

Grating patterns with a sinusoidal luminance profile were

presented in a visual "oddball" paradigm. The rare stimulus differed only in contrast from the frequent stimulus. In the electrophysiological study, the latency and amplitude measures were obtained for each value of the $\Delta C/C$ fraction (C = the frequent stimulus).

In the psychophysical study, the two-alternative forced-choice method was used because it is essentially independent of threshold criterion. The observer's task was to indicate in which interval a higher (or lower) contrast was presented. The observer's task in the electrophysiological study was to silently count the rare stimulus. This procedure provided a similar method of stimulus presentation for both studies. The just noticeable difference (JND) of contrast discrimination derived by the two methods was compared.

The P3 data indicated: 1) That P3 latency and amplitude varied with contrast difference. The latency of the N2 and P3 increased while the peak-to-peak amplitude decreased with a decrease in $\Delta C/C$. 2) The relationship between P3 latency and ΔC was more robust than either the N2 latency or the peak-to-peak amplitude. Amplitude was greater and the P3 latency earlier at the P_Z electrode site than at the Z_{63} electrode site. 3) The level of the frequent contrast had an effect on the ERP measures.

The results obtained in the psychophysical study were consistent with the results obtained in the P3 study in that frequent contrast had an effect on the JNDs. The JNDs and the variability around the means decreased with higher frequent contrast.

TABLE OF CONTENTS

Page

Page

Page

LIST OF TABLES

Page

LIST OF FIGURES

Page

Page

Page

Page

Chapter 1. Summary of the dissertation

Scalp recorded event-related potentials (ERPs) can be classified according to whether they are strictly determined by the properties of the evoking stimulus or are emitted as a correlate of an internal psychological operation. Primary visual evoked potentials (VEPs), recorded from the occipital region, are the responses of sense organs to events that occur in the external world, which means they are stimulus dependent and are largely independent of the state of the observer. Latency and amplitude of the VEP depends on stimulus parameters such as checkerboard versus grating patterns, spatial frequency, luminance and contrast of the pattern, to mention a few. The P3 of the ERP is usually recorded from central electrode sites and occurs as a result of subjective evaluation of the sensation. Ruchkin and Sutton (1973) considered the P3 as the endogenous potential that is determined by subjective probabilities assigned to events in a random series, or events which are made relevant to discrimination information.

A clear relationship between the P3 and visual discrimination of simple visual stimuli has not yet been established. Several studies have shown that there is a relationship between the observer's decision regarding contrast changes assessed by psychophysical methods, and the amplitude of the primary VEP. In some of these studies the VEPs were recorded to grating patterns that switched position through 180^{0} of phase shift eight times a second (Campbell & Maffei, 1970; Campbell & Kulikowski, 1972). This produces a VEP that is similar in shape to a sinusoid, with 16 peaks and troughs within a one second epoch. The peak-to-peak amplitude was the dependent variable which varied as a function of the contrast of the pattern. In other studies the grating pattern was flashed on and off rather than counterphase modulated. These studies showed that a linear relationship existed when the amplitude of the VEP was plotted as a function of the log of the contrast of the grating pattern. Extrapolation of the regression line to zero amplitude predicted the psychophysical contrast threshold.

The influence of physical parameters on the P3 has also been investigated; the majority of these studies have used auditory stimuli. Both 2AFC and signal detection psychophysical methods have been used. In many signal detection studies threshold stimuli and omissions were equiprobable. In general, these studies showed that the P3 was elicited only to high confidence detections of the signal (Hillyard, Squires, K., Bauer, & Lindsay (1971). Signal absence correctly and confidently perceived elicited considerably smaller P3s than those elicited by signal present and confidently perceived. When intensity level and the *a priori* probability of stimulus occurrence was varied P3s were also produced to correct rejections, particularly when the tones were of a higher intensity, while P3 amplitude also increased as stimulus intensity increased (Squires, Hillyard & Lindsay, 1973, Squires, Squires, and Hillyard, 1975).

Sutton, Ruchkin, Munson, Kietzman & Hammer, 1982 investigated the auditory P3 in a two-interval forced-choice paradigm in which the subjects were asked in which interval of the trial a tone occurred, and to give confidence ratings concerning whether or not the tone occurred. One of two intensities was presented, a low tone which the subjects detected 80% of the time or a high intensity tone which the subjects detected 95-99% of the time. A positive relationship existed between P3 amplitude and level of confidence of whether or not the signal occurred. In addition, P3 was larger to the high tone and earlier to both tones when the tone was presented in the second interval, indicating that signal absence was noted in the first interval.

Johnson and Donchin (1978) found that P3 magnitude varied as a function of ΔI, where ΔI was the difference in intensity between two tones. Successful performance or unsuccessful performance on a time estimation task was indicated by the two different tones. P3 did not depend on stimulus meaning (success or miss), but rather on the stimulus difference: the smaller the difference between the two tones, the smaller the P3. Choice reaction time was also recorded to the same stimuli and it was found that performance deteriorated as ΔI decreased, as had been found in the P3 data. However, when subjects were instructed to count one of the tones and the tones were not dependent on time estimation, the P3 to the counted tone was the same for all ΔIs while the P3 amplitude to the uncounted tone was a function of the absolute intensity of the uncounted tone.

Similar relationships have been found with somatosensory evoked potentials (SEPs). Desmedt, Debecker and Robertson (1979) compared the percentage of times stimuli were detected versus the voltage of the stimuli, and they were able to generate psychometric functions which related to the SEPs recorded to the same stimuli. When the observer was instructed to attend to and count one of these intensities, a P3 was produced to that intensity which was counted. Barrett, Halliday, Halliday and Rudolf (1979) presented subjects with electrical stimuli of 14 different intensities, and asked the subjects whether or not they detected the stimuli. P3 amplitude increased when the electrical intensity increased regardless of whether or not the subjects said they detected the stimulus.

A clear relationship between ERPs and visual discrimination of simple visual stimuli has not yet been established. An observer's ability to discriminate contrast differences between visual stimuli has been assessed in the past only by psychophysical methods. The present study investigated this ability using electrophysiological methods and explored the relationship between the electrophysiological method and the psychophysical method of human contrast discrimination.

Method

Subjects

Three unpaid female volunteers experienced in electrophysiological studies were the observers in this study. They had no history of neurological disorder and Snellen visual acuity of 20/20 in each eye (spectacle correction was used in two observers).

Stimuli

The stimuli for both the electrophysiological and psychophysical studies were sinusoidal grating patterns generated on a Cathode Ray Tube (CRT) unit. Sinewave grating patterns are the simplest visual stimuli, they can be used through Fourier synthesis to build up any complex image. Most other types of stimuli, when passing through the eye are changed because of blur and scatter. The sinewave pattern is imaged as a sinewave pattern on the retina, blur and scatter cause only a loss of contrast (Shapley & Lennie, 1985). The sinewave is one-dimensional in luminance and contains one frequency. A single spatial frequency, 2.3 cycles per degree (cpd), was used in this study. The change in luminance from dark to light bars is sinusoidal and the edges appear fuzzy, as opposed to square wave luminance changes of discrete bars. One cycle of a grating is defined as a pair of one dark and one light bar. Spatial frequency is defined by the number of cycles per degree of visual angle. The field size subtended nine degrees of visual angle with a fixation point at the center of the screen, and the viewing distance was 144 cm. Six contrasts served as the standard (frequently presented) contrast, they were 5%, 10%, 20%, 30%, 40% and 50%. Contrast is defined as the difference between the maximum luminance (Lmax) and the minimum luminance (Lmin) divided by their sum:

$$(Lmax-Lmin)/(Lmax+Lmin).$$

The mean luminance (170 cd/m^2) remained constant; as contrast was reduced, the dark bars became lighter and the light bars became darker. When the pattern was off, the luminance of the homogeneous field equalled the mean luminance of the pattern. The CRT screen was surrounded by a circular field to eliminate flicker at the edges of the display. The luminance of the testing room was dimmed to equal the luminance of the display; this avoids the confounding of light and dark adaptation. There was no change in luminance throughout the testing sessions.

<u>Procedure</u>

In the ERP study, the vertical grating patterns were presented at a rate of 1 Hz (on for 500 msec and off for 500 msec).

Each of the six contrast levels of the standard stimulus was presented as a frequent stimulus. Between seven and thirteen different contrasts were randomized and presented with each standard as the rare (target) stimulus so that the smallest differences between contrasts above, and below, the standard did not yield a P3 while the larger differences yielded P3s that resemble those seen in the literature. Within each condition, the presentation of one rare contrast and one frequent contrast was controlled by the computer in an "oddball" paradigm at a 9:1 ratio. During each condition, the observer's task was to count the number of rare presentations. For each frequent contrast, when the difference in contrast between the frequent and the rare stimuli did not produce a P3, then smaller contrast differences were not tested. The smallest difference between the stimuli that resulted in a P3 was considered threshold (ERP-JND) for each standard contrast. The absence of a P3 concurred with errors in the observer's count of the rare stimulus.

The difference in contrast between the frequent stimulus and each rare stimulus was converted to $\Delta C/C$ for each frequent contrast. This normalization was performed because equal contrast differences between the two stimuli at different frequent contrasts have different ratios. Expressing the results in reference to $\Delta C/C$ permitted the comparison of a standard psychophysical term, the Weber's ratio, with the ERP results.

Recording

Prior to applying the electrodes, the skin was rubbed vigorously with alcohol pads, then Grass Instrument EC2 cream was applied to the scalp and gently abraded. The cream was put into gold cup electrodes, and gently pressed onto the scalp.

Recordings were obtained from midline sites P_Z in the 10/20 EEG system, and an electrode site we call Z_{63}, referred to linked mastoids. P_Z and Z_{63} are midline scalp sites, 30% and 63% of the distance between the inion and the nasion. The forehead was grounded. Inter-electrode resistance was verified several times within each testing session and kept below 6K ohms.

EOGs were monitored in one observer, during two separate sessions, by electrodes placed on the inferior and supraorbital ridges. There was no effect of eye movements on the rate of artifact rejection or on the shape of the waveforms in this observer. The observers in this study were highly experienced and understood the effects of contamination by eye movements. The CRT unit has a point that the observer must fixate in order to ensure that the stimuli will be seen and processed. The task in this study is such that one does not expect eye movements to occur, because both the rare and frequent stimuli were presented at the same retinal location and both must be processed in order to distinguish between the target and non-target stimuli. For these reasons, EOGs were not monitored in the other observers.

Signals were amplified 50,000 times with a Grass P511 preamplifier with a bandpass of 0.3 Hz to 100 Hz and a 60 Hz notch filter, and viewed on a signal averager.

Signals were summated separately for the frequent and rare presentations. When the rare stimulus was presented, the EEG signals were automatically routed to and summated on a separate channel.

The signals were plotted on an X,Y plotter with positivity recorded at the active electrode and plotted in a downward direction. The length of each epoch was 768 msec, and started at stimulus onset. The sample rate for each point was 1.5 msec.

Each condition was one recording period of 512 presentations which consisted of around 462 presentations of the frequent stimulus and around 50 presentations of the rare stimulus.

Response Measurement

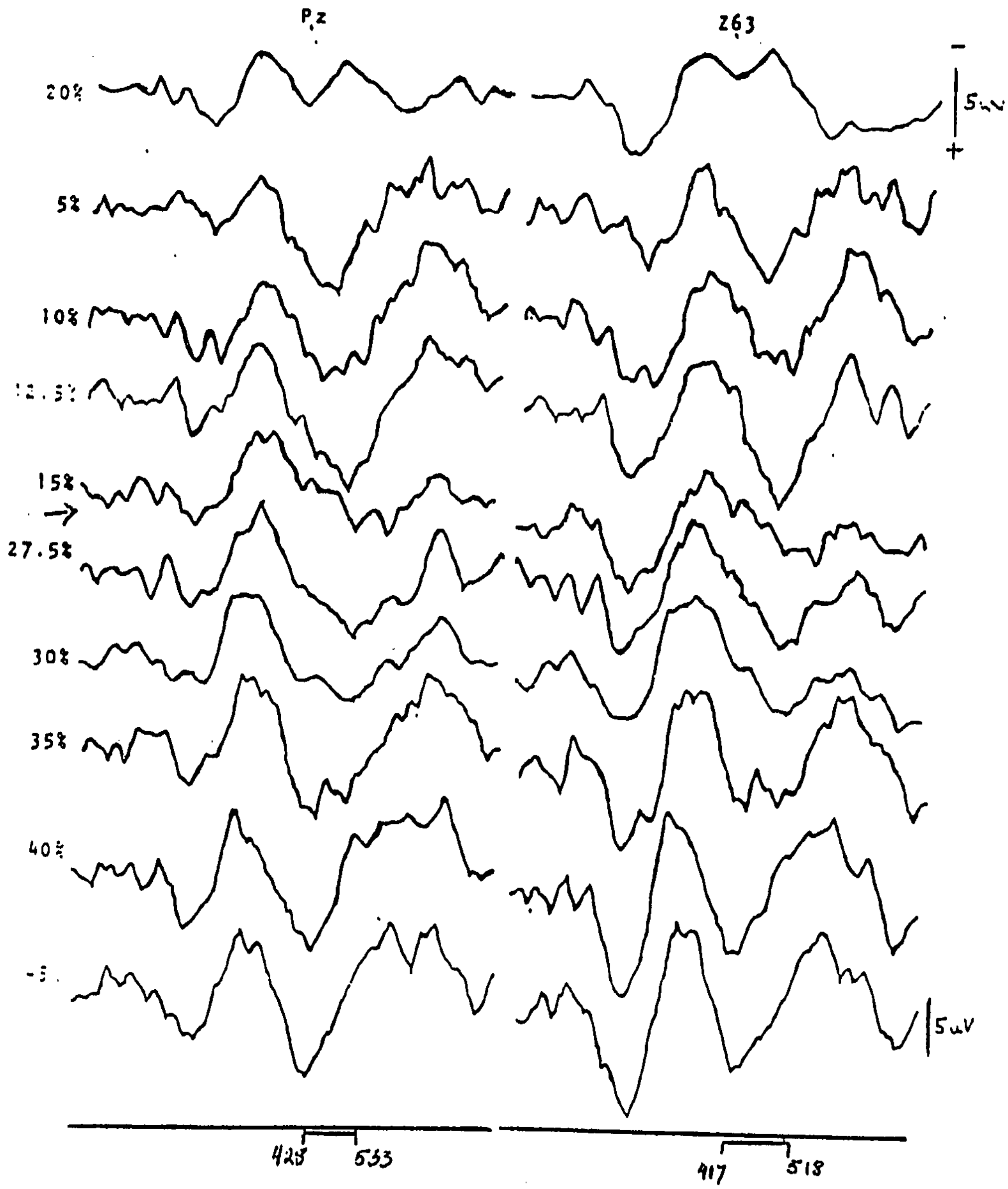
Peaks were identified in the following latency ranges: N2 (200-350 msec) and P3 (350-550 msec). Amplitude was taken as the voltage difference between N2 and P3. If a P3 appeared to be absent upon visual inspection, then the deflections in the waveform that occurred within the 350-550 msec latency range were compared against the maximum excursion within the first 10 msec of the epoch. If a deflection within the 350-550 msec latency range did not exceed three times the maximum excursion within the first 10 msec, then a P3 was considered to be absent. In each case, when a P3 was not visible in the waveform, the observer gave an inaccurate report of the number of rare stimulus presentations.

Results

P3 waveforms which resembled those seen in the literature were obtained from all three observers.

Figure 1 is an example of the traces obtained from one observer (M). The top traces were obtained to the presentation of the frequent

Figure 1. An example of the traces obtained from one observer (M) when the frequent contrast was 20%. The top traces are to the frequent stimulus, and is a summation of 462 stimulus presentations. The traces on the left were recorded from the Pz electrode site and on the right from the Z63 electrode site, both were referred to linked mastoids. The remaining traces are to the rare stimuli; each trace is the sum of 50 stimulus presentations. The latency difference between the earliest and the most delayed P3 is indicated under the traces. The numbers to the left of the traces indicate the contrast of the pattern, not the contrast difference between the two patterns. The arrow between the rare traces of 4 and 7.5 indicates where in the sequence of the rare traces the frequent contrast would be.


Pz
263
20%
5%
10%
12.5%
15%
27.5%
30%
35%
40%
5uV
5uV
428
533
417
518

stimulus which had 20% contrast. This trace is the summation of 462 stimulus presentations. The traces on the left were recorded from the P_Z electrode site and on the right from the Z_{63} electrode. The top left trace shows the evoked potential to the onset of the stimulus, but does not show a P3 response. The ERPs below the frequent waveforms are to the rare stimuli and they are the summation of 50 stimulus presentations; they are different in shape from the frequent trace, with evident N2s and P3s.

Latency of the N2 and P3 and the N2-P3 peak-to-peak amplitude were plotted as a function of $\Delta C/C$ and regression lines were fitted for each person at each standard contrast. Sixty-seven of the 68 regression lines fitted for latency versus the $\Delta C/C$ had negative slopes, indicating that as the difference in contrast between the rare and the frequent patterns increased, the latency of the N2 and P3 decreased. Figure 2 shows how P3 latency varied as a function of $\Delta C/C$ for one observer (G) when the frequent contrast was 30%. Regression lines that were fitted to the peak-to-peak amplitude versus $\Delta C/C$ were positive for 28 of 34 plots indicating that amplitude increased as the $\Delta C/C$ increased. The steepest slopes were for the frequent contrasts of 30%, 40% and 50%. Frequent contrast had a significant effect on the slopes plotted for P3 latency as a function of the $\Delta C/C$; $F(5,20) = 4.745$, $p = .0051$. The slopes plotted for amplitude as a function of the $\Delta C/C$ and the slopes plotted for N2 latency versus $\Delta C/C$ did not reach significance. There

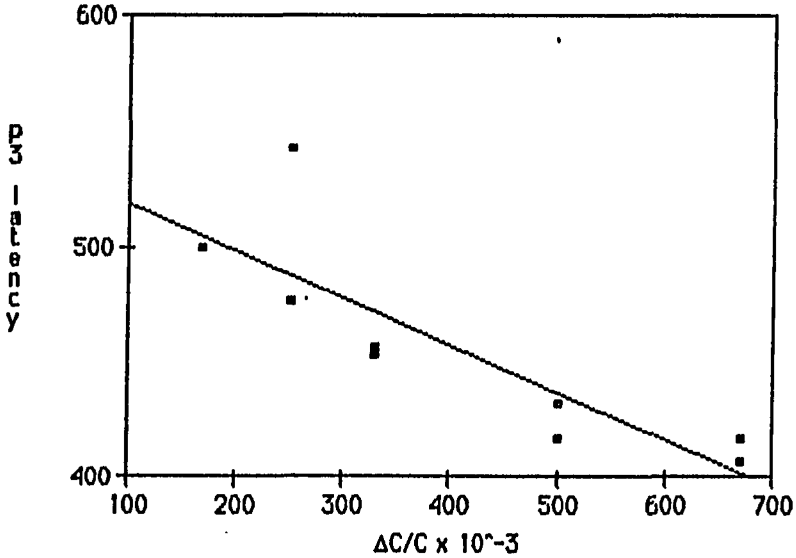


Figure 2. P3 latency plotted as a function of ΔC/C for one observer when the frequent contrast was 30%. The latency of P3 decreased as the ΔC/C increased.

was no difference between the electrode sites for any of the dependent measures.

The minimum $\Delta C/C$ that the observers required to produce waveforms with evident P3s were considered the event-related potential - just noticeable difference (ERP-JND). An inverse relationship existed between the ERP-JND and frequent contrast, the ERP-JNDs and the variability decreased as the standard contrast increased. Across observer averages of the ERP-JNDs plotted as a function of the standard contrast is show in Figure 3 (top), which also shows the JNDs obtained in the psychophysical study (bottom).

In summary, the results showed that ERPs provide an electrophysiological correlate of suprathreshold visual contrast discrimination. The results showed: 1) P3 waveforms that resemble those seen in the literature were obtained from the observers. P3s were not evident in the traces elicited to the frequent stimulus. 2) As the contrast difference between the rare and frequent patterns increased, the latency of N2 and P3 decreased and the amplitude increased systematically. 3) Frequent contrast showed an effect on the slopes of the regression lines plotted for these data. The inclinations of the slopes of the regression lines increased from 5% to 50%. This effect was more robust for P3 latency than either N2 latency or peak-to-peak amplitude.

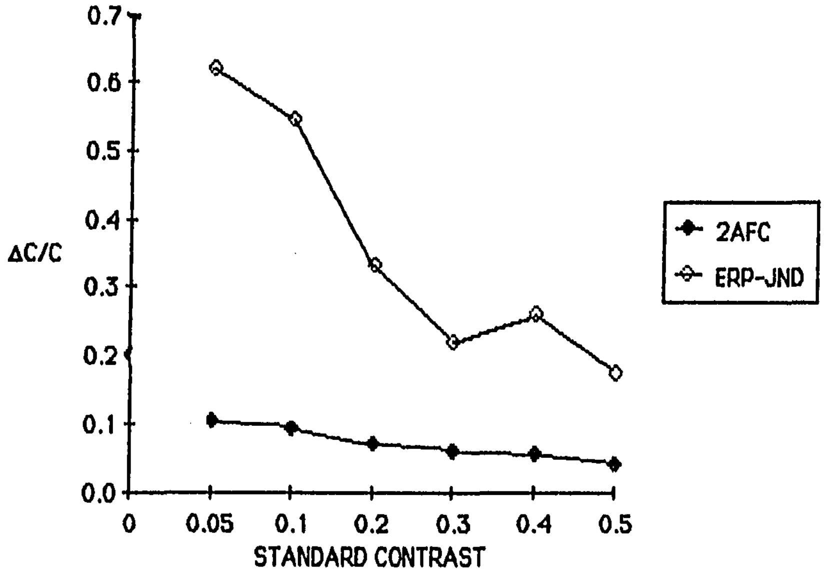


Figure 3. Across observer averages of the JNDs as a function of the standard contrast. The top shows the ERP-JNDs and the bottom the JNDs obtained in the psychophysical study.

PSYCHOPHYSICAL STUDY

This experiment was conducted in order to gain information concerning the relationship between psychophysical and electrophysiological measures of contrast discrimination in the visual system.

METHOD AND PROCEDURE

The subjects and the stimuli in this experiment were the same as those in the electrophysiological study.

The method of constant stimuli was employed; the patterns were presented using the two-alternative forced-choice (2AFC) procedure. This procedure is a psychophysical method which essentially eliminates the need to deal with the observer's criterion (Green & Swets, 1966).

The sinusoidal grating patterns were generated on the same CRT unit used in the electrophysiological study. The gratings were presented using a two interval temporal forced-choice procedure. Each interval was announced by an auditory tone. The stimuli were computer generated so that within each trial a standard pattern was presented with one comparison pattern; each was likely to occur in either of the two intervals. Each session consisted of 500 two-interval trials. The observer had to indicate which interval had either the higher contrast or the lower contrast, depending on the task in the session. At the end of the second interval, a tone signaled that a response should be made. The observers indicated their choice by pressing one of two response keys which represented the first or the second interval. The data were collected and analyzed by the computer.

Nine contrasts of the comparison stimuli were presented with each standard. The highest comparison stimulus was judged higher than the standard in over 95% of the trials and the lowest comparison stimulus was judged lower than the standard in over 95% of the trials. Step size was determined by the formula: (maximum contrast-minimum contrast)/8, which gave equal contrast intervals between the comparison stimuli.

Data Analysis

Psychometric functions were plotted. The contrast values corresponding to 25% and 75% correct were obtained from each psychometric curve and taken as the difference thresholds in order to get Weber's ratios. ANOVAs were performed on the slopes of the area of uncertainty (between the upper limen and the lower limen).

Signal detection analysis was not employed because: 1) the observers produced few errors, 2) the criterion was not varied and 3) only one single pair of hit and false alarm probabilities could be determined for each ROC curve. It is known that the area of the ROC curve which has been estimated by a single pair of hit and false alarm probabilities is not as sensitive as the proportion of correct responses in a 2AFC task (McNicol, 1972; Green & Swets, 1966).

Results

The expected result (Stevens, 1951; Gescheider, 1976; Kling & Riggs, 1972), that the $\Delta C/C$s are larger at low standard contrast levels (i.e., near threshold), were obtained; when the standard contrast was 5% the $\Delta C/C = .102 \pm .03$, while at the 50% standard the $\Delta C/C = .039 \pm .005$. Standard contrast showed a strong effect on the $\Delta C/C$; $F(5,15) = 12.668$, $p = .0001$. In addition, the variability decreased with increased standard contrast. There was no effect of observer or type of response on the $\Delta C/C$.

COMPARISON OF THE RESULTS OBTAINED IN BOTH STUDIES

A larger difference in contrast between two patterns was required to elicit a P3, than the difference limen obtained in the forced-choice paradigm. The minimum amount of contrast that an observer required to elicit a P3 was greater than the contrast corresponding to 95% correct on each psychometric curve. In addition, the regression lines describing the JNDs were not parallel, with the regression lines describing the ERP-JNDs steeper than the regression lines describing the psychophysical JNDs on a linear plot. This relationship is apparent on Figure 3 which shows the JNDs obtained in both studies at the six standard contrasts.

Similarities between the studies was shown in that they both revealed the same trends. As the standard contrast increased the $\Delta C/C$s and the variability around the means decreased.

DISCUSSION

The results of this investigation demonstrated that changes in P3 latency and amplitude reflected visual contrast discrimination processing. I demonstrated that latency and amplitude of the ERP varied as a function of the contrast difference between two stimuli that were identical in every parameter but contrast.

The data were consistent with Donchin and Isreal's (1980) assertion that P3 latency provides a measure of the time it takes to categorize events. (We can assume that the frequent and the rare stimuli fall into two distinct categories.) As the differences in intensity between the frequent and the rare stimuli became smaller, the ability to discriminate between the two stimuli became difficult, therefore the events took longer to categorize.

In addition to the latency changes seen in the P3, N2 latency also varied, and was dependent on the contrast difference between two stimuli: as the amount of contrast between the frequent and the rare stimuli increased, the N2 latency decreased. The N2 observed in this study may be a component of the negative-positive wave complex "N2-P3b" described by Squires, Squires and Hillyard (1975) and Snyder and Hillyard (1976) in an active attention condition, since N2 latency varied with P3 latency and was elicited at the same electrode site. In each instance, when P3 was elicited, it was preceded by N2.

The amplitude, as well as latency, reflected contrast differences between the two stimuli. The amplitude increased as the amount of contrast between the frequent and the rare stimuli increased. A positive relationship was obtained between amplitude and the ΔC. However, discrimination processes were reflected more in P3 latency than amplitude. This may be due to the nature of the amplitude measurement, which is supposed to reflect subjective probability of the eliciting event.

Discrimination Threshold

At the discrimination threshold (which is the smallest contrast difference between two stimuli that elicited a P3) the stimulus may become ambiguous; and one can ask whether false alarms occurred. A positive statement cannot be made of whether or not they occurred. However, we can assume false alarms did not occur because the smallest contrast differences between the frequent and the rare contrasts necessary to produce a P3 fell above 95% correct on the psychometric curves, and the observers gave accurate counts of the number of rare stimulus presentations whenever a P3 was elicited.

One of the reasons that there was a difference between the JNDs obtained in the two studies may be whether or not a full analysis of the stimulus occurred. According to Rösler, Sutton, Johnson, Mulder, Fabiani, Plooij-Van Gorsel & Roth, 1986, the P3 reflects encoding, memory comparison and decision along with some kind of an internal feedback mechanism . In other words, the identification of the target and the emission of P3 requires a rather full analysis of the stimulus and a comparison against target representations in memory (Hillyard, Picton & Regan, 1978). The JND obtained in the 2AFC study may represent two of these information processing mechanisms, encoding and memory comparison while eliminating the feedback mechanism since the observer is forced into making a decision without internal or external feedback provided. We can assume that full analysis of the stimulus did not occur since feedback was not provided. When the observer was forced into a choice, it seemed that the encoding and memory mechanisms were all that were necessary for a correct choice.

This was the first ERP study that varied the contrast of sinusoidal grating patterns of identical spatial frequency, orientation, luminance and locus in the visual field around more than one frequent contrast, while psychophysical and ERP JND thresholds were obtained, as well as the functional relationships between the latency and amplitude of the ERP and the ΔC.

Chapter 2. Introduction

How sensitive is an observer to differences in intensity of a visual stimulus? Weber (1834) described the psychophysical principle that for a given stimulus dimension, the difference threshold (DL) bears a constant ratio to the point on the dimension (the standard stimulus) at which the DL was measured.[1] For every stimulus intensity (I), there is some constant percentage of stimulus intensity that must be added or subtracted for a difference to be detected ($\Delta I/I = K$). The relationship between physical energy and mental events became known as Weber's law. Weber's law holds over the middle range of stimulus intensities, but breaks down when the standard stimulus is very weak or very strong. Based on Weber's work on the difference limen, Fechner (1860) proposed methods for measuring the relationship between subjective and objective qualities. He differentiated between the stimulus dimension (Ø) and the sensation dimension; he assumed that all just noticeable differences (JNDs) were equal psychological increments in sensation magnitude regardless of the size of ΔØ (Gescheider, 1976). Fechner is considered the founder of psychophysics.

With advances in technology, other methods of determining

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[1] Weber's studies were based on touch and kinesthesis.

observers' responses were developed. Caton (1875) was the first to identify the spontaneous electrical activity of the brain. In 1929, Berger reported his recordings of the electroencephalogram of man. With scalp electrodes, he was able to record the electrical activity of neuronal ensembles distant from the recording site. More recently, with proper stimulation and proper averaging techniques cortical responses to the occurrence of specific stimuli could be recorded.

Scalp recorded event-related potentials (ERPs) can be classified according to whether they are strictly determined by the properties of the evoking stimulus (exogenous) or are emitted as a correlate of an internal psychological operation (endogenous).[2]

Primary visual evoked potentials (VEPs) are the responses of sense organs to events that occur in the external world, which means they are stimulus dependent and are largely independent of the state of the observer. Latency and amplitude of the VEP depends on stimulus parameters such as checkerboard versus grating patterns, spatial frequency, luminance and contrast of the pattern, to mention a few.

ERPs, specifically the P300, occur as a result of subjective evaluation of the sensation.[3] Ruchkin and Sutton (1973) considered

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[2] The ERP is defined as the endogenous potential, and the evoked potential (EP), as the exogenous potential.

the P300 as the endogenous potential that is determined by subjective probabilities assigned to events in a random series, or events which are made relevant by providing feedback to discrimination information. For instance, according to Squires, Donchin, Squires and Grossberg (1977):

> Since the P3 is a multifaceted measure whose amplitude, latency and distribution over the scalp may be independently determined by different aspects of the cognitive process, it might well prove to be a richer measure than such traditional indices of processing as reaction time (RT). For example, P300 latency may index the time of occurrence of a cognitive process, its scalp distribution may index the nature of the task and P300 amplitude may index expectancy for the eliciting event. (p. 299)

A clear relationship between ERPs and visual discrimination of simple visual stimuli has not yet been established. An observer's ability to discriminate contrast differences between visual stimuli has been assessed in the past only by psychophysical methods. The present study investigated this ability using electrophysiological methods and explored the relationship between the electro-physiological method and the psychophysical method of human

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[3] The terms P300 and P3 are mentioned to as they are referred to in the original journal articles. For this study the term P3 is used, though in the visual modality its latency is around 450 msec.

contrast discrimination. An aim of this study was to investigate if ERPs can provide an objective means of contrast discrimination in observers who would be difficult to test with psychophysical procedures and also to overcome observer bias which can effect psychophysical results.

Electrophysiological Studies

Primary evoked potentials and contrast. Several studies have shown that there is a relationship between the observer's decision regarding contrast changes and the amplitude of the primary VEP. Visual evoked potentials elicited by presenting grating patterns of different levels of contrast have been compared to psychophysical data obtained from the same stimuli. In most of these studies the evoked potentials were recorded to grating patterns that switched position through 180° of phase shift eight times a second. This produces an evoked potential with 16 peaks and troughs, within a one second epoch, that is similar in shape to a sinusoid. The peak-to-peak amplitude of the evoked potential is the dependent variable which varies as a function of the contrast of the pattern. Campbell and Maffei (1970) compared the contrast threshold obtained by psychophysical methods with the VEP and found that a linear relationship existed when the amplitude of the VEP was plotted as a function of the log of the contrast of an 8 Hz counterphase grating pattern, and that extrapolation of the regression line to zero amplitude predicted the psychophysical contrast threshold. The same results were found when the grating pattern was flashed on and off rather than counterphase modulated (Campbell & Kulikowski, 1972). Cannon (1983) obtained VEP/contrast sensitivity functions by continuously attenuating the contrast during the VEP recording until the signal-to-noise ratio in the average was 1.25 - 1.3 of the response (the averaged EEG), and found that a positive correlation existed between the extrapolated evoked potential threshold and the just noticeable contrast.

Bodis-Wollner, Hendley and Kulikowski (1972) studied contrast modulation of a 6 cycle per degree (cpd) sinusoidal grating pattern, which was temporally modulated at the rate of 8 Hz. In the contrast modulation paradigm, the contrast was incremented by a fixed amount of contrast for 125 msec and then decremented by the same fixed amount of contrast for 125 msec which gives eight presentations of a fixed amount of contrast alternating with eight of that amount plus the increment. The contrast increased or decreased without changing spatial location. The VEP had the greatest amplitude when the contrast modulation depth was 100% (the pattern appears and disappears), and the amplitude decreased as the depth of modulation decreased; in other words, the smaller the difference between the two contrasts, the smaller the amplitude. Psychophysical data (frequency of seeing the difference between two contrasts) was obtained on the same observers. Their results suggested that VEP threshold data are correlated with psychophysical threshold data for the same stimuli.

P300 and psychophysical studies.

It has been established "that the physical parameters of the eliciting stimulus have a profound influence on the human average evoked potential waveform, particularly on components occurring within 250 msec of stimulus presentation." (Pritchard, 1981, p. 506). The influence of physical parameters on the P3 has also been investigated (the majority of these studies have used auditory stimuli). The following studies will show that *a priori* probability and task relevence are not the only variables that determine the magnitude of P3s.

Forced Choice. Sutton, Ruchkin, Munson, Kietzman and Hammer (1982) investigated the auditory P3 in a two-interval forced-choice paradigm in which the subjects were asked to report in which interval of the trial the signal (a tone) occurred, and to give confidence ratings concerning whether or not the signal occurred. One of two intensities was presented, a Lo intensity tone which had an 80% accuracy level or the Hi intensity tone which had a 95-99% accuracy level. They found that a positive relationship existed between P3 amplitude and the level of confidence of whether or not the signal occurred. In addition, the results indicated clear differences as a function of the observation interval in which the signal was presented. The P3 amplitude was largest in response to high-confidence detection of the presence of the signal (Hi tones), and occurred in the interval in which the tone was presented. P3 latency to low intensity tones was longer than to high intensity tones in both intervals. However, the P3 was 100 msec earlier when the signal occurred in the second interval, which suggested that signal absence in the first interval had been noted. These authors proposed that the point in the trial (either the first or the second interval) at which the largest P3 would be obtained might indicate the nature of the subject's detection strategy. The results suggested that the subjects used different strategies at high and low confidence levels. For high-confidence detections, serial independent detection seemed to be the strategy and for low-confidence detections, a comparison of the percepts seemed to be the strategy. The present dissertation assumes that high-confidence detections are reflected in shorter latencies and larger amplitudes of the P3, although the evidence of Sutton, et al on this point was not conclusive since the observers did not indicate which stimulus was presented after each presentation.

Signal detection. In an auditory signal detection paradigm, a clear relationship has been found between P3 and d'; d' and P3 elicited on HIT trials increased as the intensity of the signal increased until the detection level was about 90% correct (d' around 2.5). (All of the signals presented were near the psychophysical threshold.) Above this high accuracy level, P3 decreased while d' increased (Hillyard, Squires, Bauer, & Lindsay, 1971). Signal absence correctly and confidently perceived elicited considerably smaller P3s than those elicited by signal present and confidently perceived. Hillyard, et al. suggested these results were obtained because the sensory input is evaluated by comparing it with a 'template' of the signal in memory, and that P3 is elicited when a match occurs between the sensory input and the template for the signal. The amplitude of P3 increased with the closeness of the match of the input with the template. They also suggested that the subject does not have a template for "no signal". They reasoned that P3 declined as the d' increased above a certain level because the subject considered that the stimulus event was likely to occur. The *a priori* probability of stimulus occurrence was .5, which is considerably higher than P3 studies with frequent and rare stimuli. One can consider what would have happened if the probability of these correctly and confidently perceived stimuli were presented at a low rate; perhaps then P3 would have further increased with d'.

However, when the stimulus intensity was held constant, at near threshold, only correctly detected stimuli evoked P3s. False alarms, correct rejections and misses did not elicit a P3 (Squires, Hillyard & Lindsay, 1973). In this study the subjects rated (on an 8-point scale) whether or not an auditory signal was presented.

In 1975 Squires, Squires and Hillyard added a marker light to indicate tone presentation time, whether or not it was presented. They had subjects rate whether or not a near threshold signal was present on the same 8-point rating scale as Squires, et al (1973) and found P3's on high confidence false alarm trials as well as on HIT trials. The P3s were of similar latency and amplitude. They concluded that by adding a marker light to precisely define the observation interval and by sorting the ERPs on the basis of confidence ratings, high-confidence false alarms produced P3s as large as high-confidence correct detections. Therefore, they concluded that for near threshold auditory stimuli, whether or not the signal was presented, signal present decisions produce P3s. (In this and the above studies signals were presented in 50% of the trials.) In the same study, they increased the intensity level and *a priori* probability of the signal and found that correct rejections had larger P3 amplitudes than HITs. This occurred because the *a priori* probability of the missing stimulus was .1 and the signal was well above threshold.

In another study published in the same year (Squires, et al., 1975c), the authors again used an 8-point scale, but investigated the effect of *a priori* probability of near threshold signal presentation. The results of this study indicated P3 amplitude associated with high-confidence HITs increased as signal probability increased.

The results of these studies showed that intensity level affects whether or not a P3 will be elicited. P3 for high-confidence correct detections are greater for threshold than suprathreshold stimuli. Probability of occurrence has different effects on the P3 depending on intensity, probability of presentation of near threshold stimuli produced larger P3s than suprathreshold stimuli presented at the same probability. Stimulus absence produces larger P3s when the suprathreshold stimulus is presented on 90% of the trials.

Ruchkin, Sutton, Kietzman and Silver (1980) were interested in the measurement of P3s elicited by low signal intensities because of the relatively small and poorly defined P3s that occur at low intensities, and because P3 latency tends to increase as detection accuracy decreases. They reexamined the Hillyard, Squires, Bauer and Lindsay 1971 paradigm (above) which showed that with near threshold auditory stimuli above a certain high d' level, as d' increased P3 decreased. In the Ruchkin, et al study, after a suprathreshold warning click, a second click was presented in 50% of the trials. The second click had one of three intensities; the subjects had to report whether or not a click occurred and their degree of confidence. The results indicated very few miss and false alarm responses for the high and middle intensity tones. P3 amplitude increased with higher intensity clicks, however since there were only three intensities presented, it is conceivable that Hillyard's study would have been replicated with more intensity levels. (By using PCVA they were able distinguish P3s from slow waves which often overlap when low intensity stimuli are used.) They also found slow wave amplitude decreased with increasing accuracy.

As opposed to the above studies which used near threshold auditory stimuli, the present dissertation investigated the just noticeable difference threshold of visual stimuli. As we shall see, the P3 jnds were considerably higher than psychophysical jnds. P3s did not occur until the ΔIs were above 95% correct on the psychometric curves.

Other psychophysical methods. Johnson and Donchin (1978) found that P3 magnitude varied as a function of ΔI, where ΔI was the difference in intensity between two tones. Successful performance (S+) or unsuccessful performance (S-) on a time estimation task was indicated by the two different tones. P3 did not depend on stimulus meaning (success or miss), but rather on the stimulus difference: the smaller the difference between the two tones, S+ and S-, the smaller the P3. Choice reaction time was also recorded to the same stimuli and it was found that performance deteriorated as ΔI decreased, as had been found in the P3 data. However, when subjects were instructed to count one of the tones and the tones were not dependent on time estimation, the P3 to the counted tone was the same for all ΔI's while the P3 amplitude to the uncounted tone was a function of the absolute intensity of the uncounted tone. Ritter, Simson and Vaughan (1972) also found that P3 varies in latency as a function of the degree of difference between frequent and rare stimuli.

Similar relationships have been found with somatosensory evoked potentials (SEPs). Desmedt, Debecker and Robertson (1979) compared the percentage of times stimuli were detected versus the voltage (intensity) of the stimuli, and generated psychometric functions which related to the SEPs recorded to the same stimuli. When the observer was instructed to attend to and count one of these intensities, a P3 was produced to that intensity which was counted. Barrett, Halliday, Halliday and Rudolf (1979) presented subjects with electrical stimuli of 14 different intensities, and asked the subjects whether or not they detected the stimuli. The results showed that P3 amplitude increased when the electrical intensity increased regardless of whether or not they said they detected the stimulus.

The P3 studies discussed above used auditory and somatosensory stimuli. There are few studies which address discrimination of stimulus strength using visual stimuli. Pfefferbaum, Ford, Johnson, Wenegrat and Kopell (1983) used visual stimuli and found that instructions (speed versus accuracy) to press a button and ease of discrimination affect the P3. Horizontal pairs of parallel lines were presented to subjects who had to indicate if these pairs were the same length or different. P3 latency was earlier when the difference between the length of the lines was larger and also when the subjects were told to respond quickly.

On the other hand, Ullsperger, Gille & Neumann (1986) found disagreement between ERPs and the psychophysical results. They presented observers with seven different Gestalt categories of computer displays that ranged from easy to discriminate from a standard pattern to difficult to discriminate from a standard pattern. The psychophysical results were in the expected direction, reaction time and frequency of errors increased with increasing task difficulty. However, they found amplitude increased and latency decreased with increasing task difficulty. Since more information is provided with increasing task difficulty, amplitude increase could have occurred, but the length of time required to process the information should be increased. In this study the ERP results were in direct opposition to the psychophysical results and other ERP studies.

Studies which investigated the P3 using simple visual patterns as opposed to letters and geometric shapes are rare. Table 1 shows the variety of visual stimuli that have been used in P3 studies. Of

Table 1

Varieties of Visual Stimuli Used in P3 Studies

STIMULI	LITERATURE
1. Names of colors printed in the same or different colors	Aine, C. & Harter, R. (1984)
2. Hebrew words composed of four letters presented with distractors	Bentin, S. & Carmon, A. (1984)
3. Numbers and letters	Chapman, R. M., McCrary, J. W., Bragdon, H. R. & Chapman, J. A. (1979)
4. Letters "A" and "B", each at the same luminance and visual angle (.5), letters "C" - "Z" presented at a smaller visual angle (.2) and lower luminance, and a novel stimulus at 2.3 c/d	Courchesne, E. (1978)
5. Light flashes against either a circle or a square background	Donchin, E., & Cohen, L. (1967)
6. Letters "H" or "S"	Duncan-Johnson, C. & Donchin, E. (1980)
7. Number "8" presented with nonsignals, numbers "2"-"19", and repetition of a preceding number	Friedman, D., Vaughan, H. G., Jr. & Erlenmeyer-Kimling, L. (1981)
8. Green circle and a white ring presented in different visual fields	Harter, R., Aine, C. J. & Schroeder, C. (1984)
9. Easy and degraded letters	Kok, A. (1980)
10. Sentences	Kutas, M. & Hillyard, S. A. (1984)

STIMULI	LITERATURE
11. Letters with closed loops vs open loops and letters that rhyme with "V"	Lovrich, D., Simson, R., Vaughan, H. G., Jr. & Ritter, W. (1986)
12. Parallel lines of the same and different lengths	Pfefferbaum, A., Ford, J., Johnson, R., Jr., Wenegrat, B & Kopell, B. S. (1983)
13. Varied circle size and triangle shape	Rösler, F. (1981)
14. Single and double light flashes	Ruchkin, D. S. & Sutton, S. (1979)
15. Sinusoidal grating patterns of two spatial frequencies	Schechter, G., Callaway, E., Halliday, R. & Naylor, H. (1986)
16. Alphanumeric and geometric presentations	Skrandies, W., Chapman, R. M., McCrary, J. W. & Chapman, J. A. (1984)
17. Arrows pointing left or right, difficult vs easy colored discs compared to similar auditory tasks	Squires, N. K., Donchin, K.C., Squires, K. C. & Grossberg, S. (1977)
18. Pictures and words	Stuss, D. T., Leech, E. E., Sarazin, F. F. & Picton, T. W. (1984)
19. Letters alternating with random dot displays	Thatcher, R. W., (1977)
20. Vertical and horizontal striped patterns	Towle, V. L., Sutcliffe, E. & Sokol, S. (1985)
21. Gestalt computer displays	Ullsperger, P., Gille, H-G. & Neumann, U. (1986)

the 21 studies shown, only two investigated the ERP using grating patterns. Towle, Sutcliffe and Sokol (1985) presented square wave patterned stimuli vertically and horizontally to normal subjects and three patients. Two patients were diagnosed as malingerers and the other patient was diagnosed as being hysterically blind. The normal subjects had P3s to the rare stimuli and correctly counted the number of rare presentations, while the patients had lower amplitude P3s and gave inaccurate counts of the rare stimuli. Since the patients produced P3s, the authors concluded that P3 would be a valuable tool which could differentiate between the types of patients in this study and those patients with visual deficits. Whereas, Schechter, Callaway, Halliday and Naylor (1986) investigated the differences in reaction time (RT) and P3 latency as functions of spatial frequency of sinusoidal grating patterns. Patterns with two spatial frequencies, .8 (low) and 8 (high) were presented randomly at equal probabilities, and the subjects had to release a response key to each stimulus presentation. ERPs were recorded simultaneously. Both RT and P3 latency showed similar, changes as a function of spatial frequency; faster RTs and earlier P3 occurred with low spatial frequency.

In pilot work we examined the effect of the contrast difference between a frequent and a rare grating pattern. Probabilities were held constant at 9:1. P3 latency varied as a function of contrast difference between two suprathreshold patterns of identical spatial frequency. This relationship can be expressed as a linear function in which latency of the P3 decreases when the difference in contrast between the two stimuli increases. However, the precise relationship of the detection and/or the discrimination of a simple visual stimulus to the shape of a psychophysical psychometric function has not yet been established.

Psychophysical Studies

The ERP is a scalp recording of decision processes; specifically, the P300 occurs as a result of subjective evaluation of the sensation. Psychophysics, on the other hand, is the study of the relationship between the subjective evaluation of the sensation and physical aspects of the stimulus. Sinewave gratings have been used to study contrast discrimination (Bodis-Wollner, Hendley, & Kulikowski, 1972; Kelly & Savoie, 1973; Franzen & Berkley, 1975; Bodis-Wollner & Hendley, 1979; Legge & Kersten, 1981). Spatial frequency (the number of dark and light pairs per degree of visual angle), manner of presentation (pattern alternates, or it appears and disappears either abruptly or slowly), and the average luminance of the display affect contrast discrimination. Regardless of the different stimulus parameters, for each parameter the relation between changes in contrast (ΔC) and the mean contrast may be plotted as the "contrast discrimination function" and the smallest value of the ΔC that allows for reliable discrimination is called the "contrast increment threshold".

Kulikowski (1976) presented observers with sinewave grating patterns of different spatial frequencies which had to be matched for contrast. Patterns of different spatial frequencies that were similarly evaluated for contrast had significantly different JNDs. The just noticeable contrast difference between the patterns depended upon the contrast threshold for each of the different spatial frequencies. Grating patterns between two and five cycles per degree of visual angle have lower contrast thresholds than patterns below two and above five cycles per degree. In addition, when contrasts of one spatial frequency were compared, the JND depended on the standard contrast, and errors increased when the standard pattern had a higher contrast.[4] When comparing the JNDs obtained from two different standard contrasts, but the same spatial frequency, the JND depended upon the standard contrast; and when two patterns of different spatial frequencies were compared the JNDs for the same standard contrasts were not the same. Therefore, he concluded that the JND cannot be a unit of sensation.

Ejima and Ohtani (1987) examined the relation between simple

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[4] As we shall see, the results of this dissertation, agree with Kulikowski, in that the JND depended on the standard contrast, but disagreed in that the errors decreased rather than increased with higher standard contrasts.

reaction time, and perceptual and response processes using sinusoidal grating patterns. In the RT study they found that reaction time decreased as contrast increased from 4 dB to 21 dB above threshold, and then gradually leveled off. In the psychophysical study, contrast thresholds were measured by the two-alternative forced-choice staircase method. Each trial consisted of two 500 msec intervals. One interval had the pattern, the other interval had a blank screen and the observer had to indicate in which interval the pattern was presented. After contrast thresholds were obtained, exposure duration (ED) of the patterns was varied from 2.3 msec to 482.3 msec and thresholds again were obtained as a function of exposure duration. By combining the results from the RT study with the results from the exposure duration study, the authors were able to determine the perceptual integration time and the transmission time for an observer to recognize the presence of a pattern. Their results showed the RT - ED difference (the perceptual integration and transmission time) of a contrast depended on spatial frequency; the observers responded faster to lower spatial frequencies. The length of time for perceptual integration and transmission was not compared to ERP components, although, since N2 has been shown to be a correlate of stimulus evaluation time; an interesting study would be to compare N2 latency with "perceptual integration and transmission time."

Statement of the Problem

Previous visual P3 studies have employed stimuli such as geometric designs (Purves, Low, & Baker, 1979), words and letters (Donchin, 1984; Friedman, Vaughan, & Erlenmeyer-Kimling, 1981), and sentences (Kutas & Hillyard, 1984). These studies proposed that the P3 represents an electrophysiological representation of subjective evaluation of the sensation. However, in addition to the differences in sensation, conceptual differences, i.e., stimuli that differed in more than one dimension, were involved in the differences between the stimuli that elicited a P3.

Sinewave grating patterns are the simplest visual stimuli, they can be used through Fourier synthesis to build up any complex image. These patterns have been used extensively to study the imaging capacity of the eye (Campbell & Green, 1965), and single visual neurons (Enroth-Cugell & Robson, 1966). Most other types of stimuli, when passing through the eye are changed because of blur and scatter. The sinewave pattern is imaged as a sinewave pattern on the retina, blur and scatter cause only a loss of contrast (Shapley & Lennie, 1985). The sinewave is one-dimensional in luminance and contains one frequency (see Figure 1, p. 24). A single spatial frequency, 2.3 cycles per degree, was used in this study. Using one spatial frequency involves one single spatially "tuned" channel from the retina to the visual cortex (Shapley & Lennie, 1985).

By employing simple grating patterns that differ only in contrast, it is possible to investigate an observer's evaluation of sensation without the confounding effects of conceptual differences. With these simple patterns, one can directly compare the P3 results with psychophysical results, thereby gaining information concerning the relationship of psychophysical and electrophysiological measures of sensation in the visual system.

Purpose of the Study

In pilot work we found that the contrast difference between two suprathreshold grating patterns affects the latency of the P3. This study further examined the role of contrast discrimination and investigated: 1) whether or not the P3 contrast discrimination threshold relates to the psychophysical function in contrast discrimination, 2) if the latency of the N2 and the P3, and the (N2-P3) peak-to-peak amplitude vary as a function of the contrast differences between two stimuli, and 3) if ERPs can provide an objective means of contrast discrimination, which 4) could provide a bridge between visual psychophysics and cognitive psychology.

Chapter 3. Method

Subjects

The three observers (M, G, and L), 31, 49 and 28 years old, including the experimenter, were unpaid female volunteers with no history of neurological disorder. Each observer had Snellen visual acuity of 20/20 in each eye (spectacle correction was used in two observers). A description of the procedures was provided on a consent form that was signed by three people: the observer, a witness and the experimenter. A copy of the consent form is provided in Appendix A. Because testing sessions lasted several hours, bite bars and artificial pupils were not used. The observers were aware of the importance of maintaining fixation and staying alert.

Stimuli

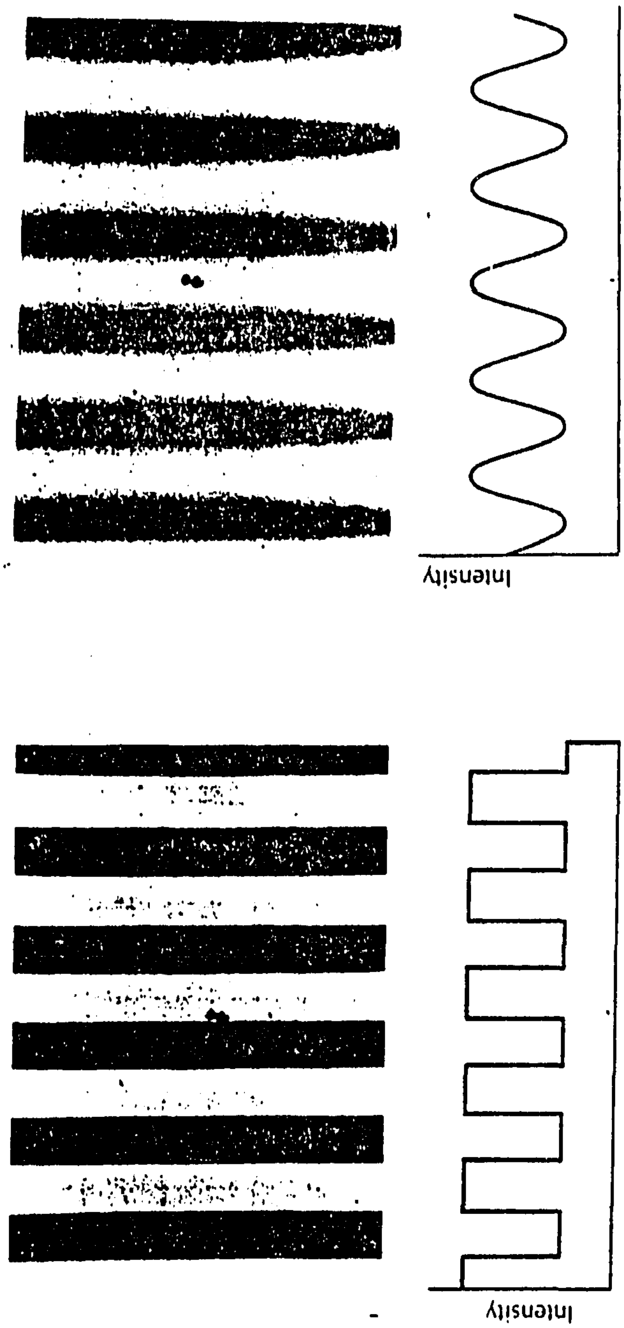
The stimuli for both the psychophysical and electrophysiological studies were sinusoidal grating patterns. The human visual system is especially sensitive to sinusoidal patterns (Carlson, 1981), particularly between 2 and 5 cycles per degree (cpd) of visual angle (Watson, Barlow, & Robson, 1983). Sinusoidal grating patterns, compared to checkerboard or square wave patterns, are reduced only in modulation; they are not changed in waveform as they pass through the optics. Sinewave grating patterns can be formed directly on the retina as interference patterns that are largely independent of the optical limitations of the eye (Campbell & Green, 1965).

The change in luminance from dark to light bars is sinusoidal and the edges appear fuzzy, as opposed to square wave luminance changes of discrete bars. Figure 4 shows sine and square wave grating patterns and the luminance profile of each. One cycle of a grating is defined as a pair of one dark and one light bar. Spatial frequency is the number of cycles per degree (cpd) of visual angle. The spatial frequency used in both studies was 2.3 cpd. The field size subtended nine degrees of visual angle with a fixation point at the center of the screen; and the viewing distance was 144 cm. The standard contrasts were: 5%, 10%, 20%, 30%, 40% and 50%. Contrast is defined as the difference between maximum (Lmax) and minimum (Lmin) luminance divided by their sum:

$$(Lmax-Lmin)/(Lmax+Lmin).$$

The mean luminance (170 cd/m^2) of the pattern remained constant; as contrast was reduced, the dark bars became lighter and the light bars became darker. When the pattern was off, the luminance of the homogenous field equalled the mean luminance of the pattern. Therefore, there was no change in luminance throughout the testing sessions. The CRT screen was surrounded by a circular field to eliminate flicker at the edges of the display. The luminance of the testing room was dimmed to equal the luminance of the display; this avoids the confounding of light and dark adaptation.

Figure 4. An illustration of a square-wave grating pattern and its luminance profile and a sinusoidal grating pattern and its luminance profile.


Intensity
Position
Intensity
Position

The stimuli were generated on a Joyce Electronics Cathode Ray Tube (CRT) unit with a P4 phosphor by Z-axis modulation. The CRT has sawtooth X and Y timebases which produce an evenly illuminated raster on the screen. All of the stimuli were within a calibrated range in which contrast is linearly related to Z-axis voltage. The CRT beam current can be rapidly modulated to enable the production of patterns suitable for research.

Calibrations

The Spectra Photometer/Radiometer 301 was employed to measure the luminance of the bars of the pattern. Measurements were taken over stationary gratings through a one millimeter slit in a cap supplied with the photometer. The photodiode was positioned in front of, and touching, the CRT; the slit was moved across the grating for the maximum and the minimum outputs of the photocell. The voltage of the maximum and the minimum outputs of the photodiode were measured and the contrast was calculated from these readings. The measured contrast increased linearly with the voltage up to 72% contrast. Calibrations were repeated several times during the year while the data were being collected.

Data collection required about nine months of testing. The psychophysiological and electrophysiological tests were presented randomly on different days. On each data collecting day, either one of the two methods was used for any one observer. Only one frequent contrast for the electrophysiological or one standard contrast for the psychophysiological testing was presented on a day.

Chapter 4. Electrophysiological Study: Procedure

Vertical grating patterns with a sinusoidal luminance profile were presented at a rate of 1 Hz (on for 500 msec and off for 500 msec).

For ERPs, each of the six contrast levels of the standard stimulus was presented as a frequent stimulus. Between seven and thirteen different contrasts were randomized and presented with each standard as the rare (target) stimulus so that the smallest differences between contrasts above, and below, the standard did not yield a P3 while the larger differences yielded P3s that resemble those seen in the literature. Within each condition, the presentation of one rare stimulus and one frequent stimulus was controlled by the computer in an "oddball" paradigm at a 9:1 ratio. During each condition, the observer's task was to count the number of rare presentations. The number of conditions tested varied between the observers. For each frequent contrast, when the difference in contrast between the frequent and the rare stimuli did not produce a P3, then smaller contrast differences were not tested. The smallest difference between the stimuli that resulted in a P3 was considered threshold (ERP-JND) for each standard contrast. The absence of a P3 concurred with errors in the observer's count of the rare stimulus. How this smallest difference was calculated will be explained later.

Recording

Prior to applying the electrodes, the skin was rubbed vigorously with alcohol pads, then Grass Instrument EC2 cream was applied to the scalp and gently abraded. The cream was put into gold cup electrodes, and gently pressed onto the scalp.

Recordings were obtained from midline sites P_Z and Z_{63}, referred to linked mastoids. P_Z and Z_{63} are midline scalp sites, 30% and 63% of the distance between the inion and the nasion, respectively. These sites were chosen because: the P_Z electrode site is a conventional site which has been used in many P3 investigations,[5] and is known to produce a P3; other sites conventionally used for P3 recordings are the frontal (F_Z and F_{PZ}) and the central sites (C_Z), Z_{63} is between C_Z and F_Z and therefore is a fronto-central location (C_Z-F_Z). The Nicolet 1170 is a four channel averager; in order to record responses to both the frequent and the rare stimuli only two electrode sites can be used at any one time. The forehead was grounded. Inter-electrode resistance was verified several times within each testing session and kept below 6K ohms.

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[5] Two of the earlier studies that did not use this electrode site were Ruchkin, Sutton and Tueting (1975) and Squires, Squires and Hillyard (1975c), they recorded from one site, C_Z.

Signals were amplified 50,000 times with Grass P511 preamplifiers with a bandpass of 0.3 (with rise time constant of .3 msec) to 100 Hz (the fall time constant was 600 msec) and a 60 Hz notch filter, and viewed on a signal averager (Nicolet 1170).

The responses in which the voltage exceeded ± 80 µV in two observers and ±160 µV in one (M) were rejected on line. In all three observers, the rejection rate was extremely low (<1%). The rejection rate was derived from the number which was displayed on the Nicolet P300 stimulator, as the number of stimuli presented, versus the number summed, which was displayed on the averager.

Signals were summated separately for the frequent and rare presentations. When the rare stimulus was presented, the EEG signals were automatically routed to and summated on a separate channel.

The signals were plotted on an X,Y plotter (Allen Datagraph) with positivity at the active electrode plotted in a downward direction.

Eye movements

Electrodes were placed around the eye inferiorly and supraorbitally to monitor EOGs in one observer (the experimenter) during two separate sessions. In this observer there was no effect of eye movements on the rate of artifact rejection or on the shape of the waveforms.

The observers in this study were highly motivated and understood the effect of contamination by eye movements. As opposed to P3 testing with auditory or somatosensory stimuli when the observer could close his/her eyes and eye movements could go undetected; the CRT unit has a point that the observer must fixate in order to ensure that the stimuli will be seen. Visual fixation also helps control for eye movements. During the recording sessions the observers were monitored for excessive eye movements. The task in this study is such that one does not expect eye movements to occur, because both rare and frequent stimuli were presented at the same retinal location. In addition, if eye movements were recorded throughout the experiment, either P_z or Z_{63} would have been eliminated. For these reasons, EOGs were not monitored in the other observers.

Contamination from eye blinks were not considered, since eye blinks are not time locked to stimulus onset; they can occur any time within the epoch recorded to either the frequent or the rare stimulus. Other artifacts that can occur at any time within an epoch are heart beats, muscle contractions or electrical interference.

All of the testing was binocular.

Each condition was one recording period of 512 presentations which consisted of around 462 presentations of the frequent stimulus and around 50 presentations of the rare stimulus.

The length of each epoch was 768 msec, and started at stimulus onset. The sample rate for each point was 1.5 msec.

Response Measurement

Latency and amplitude of the waveforms were measured by moving cursor points to the most negative and the most positive peaks and noting the locations. Peaks were identified in the following latency ranges: N2 (200-350 msec) and the P3 (350-550 msec). The Nicolet 1170 is equipped with two cursor points, each with its corresponding thumbwheel that moves the cursor along the waveform. As the cursor point is moved, the voltage level at the location of the point is displayed on a corresponding LED display. The method of obtaining the latency and the peak-to-peak amplitude is: 1) the first cursor point is placed in the area of what visually appears to be the most negative peak in the 200 to 350 msec range, the cursor is moved in that area until the most negative voltage is displayed on the LED, this also denotes N2 latency at the thumbwheel. 2) The second cursor is moved in the vicinity of the most positive peak in the 350 to 550 msec range until the most positive voltage is displayed on the corresponding LED display, this denotes latency for the P3 at the thumbwheel. 3) After the cursor points are positioned on their corresponding peaks, a button press displays a digital number that relates to the difference in voltage between the two locations on the waveform. That number is then converted to the peak-to-peak amplitude in the following manner: the displayed number is multiplied by .6153 then divided by the number of presentations summed in the waveform. This transformation was derived in the following manner: a 50μV signal was put into the Nicolet and the LED display read 30.765. For a known input signal of 50μV, and an output reading of 30.765, .6153 is derived from; 50x = 30.765, therefore, 1μV = .6153 for each presentation. Since the Nicolet summates the EEGs rather than averages them, this transformed number must be divided by the number of EEGs in the waveform to get the actual voltage between the peaks. Therefore, peak-to-peak amplitude = [(LED reading)(.6153)]/(# of EEGs). Calibrations were performed several times during the testing period.

When the P3 appeared flattened or had a "W" waveshape the center of the P3 was considered the latency, while the lowest LED number displayed in the area was the number which was used for N2-P3 amplitude calculations.

If a P3 appeared to be absent upon visual inspection, then the deflections in the waveform that occurred within the 350 - 550 msec latency range were compared against the maximum excursion within the first 10 msec of the epoch. If a deflection within the 350 - 550 msec latency range did not exceed three times the maximum excursion within the first 10 msec, then a P3 was considered to be absent. In each case, when a P3 was not visible in the waveform, the observer gave an inaccurate report of the number of rare stimulus presentations. Figure 5 illustrates traces elicited by the frequent, non-target, stimulus and examples of traces elicited by target stimuli when the P3 was absent and when the P3 was present.

Baseline-to-peak amplitude was determined as the difference between the first cursor point, placed at an arbitrary baseline, which was between one msec latency and 4.5 msec latency, and the peak. This arbitrary baseline was chosen because instrument artifacts were noted on several traces at stimulus onset. The baseline-to-P3 amplitudes were noted, but these amplitudes were smaller than the peak-to-peak amplitudes so they were not considered in the statistical analyses. The baseline-to-peak amplitude measurements could have been confounding since some of the traces resulted in polarity changes that were obvious peaks, however they were insufficient to cross the baseline. Figure 6 illustrates the differences in amplitude measured from baseline-to-peak versus peak-to-peak calculations.

Subtractions were employed to determine the differences between the frequent and the rare waveforms, as well as to remove components that are common to both waveforms (i.e., exogenous components that occur to both the onset and the offset of a visual stimulus). Another reason for obtaining subtracted traces is that in

Text continues on page 60.

Figure 5. Traces from the P_z electrode site when the frequent stimulus had a contrast of 10%. The top trace is the summation of 462 stimulus presentations. The traces beneath are to the rare stimuli, and are the summation of 50 presentations. The middle trace was to a 15% contrast pattern and does not have a P3, the bottom trace was to a 17.5% contrast pattern and clearly shows a P3 at 480 msec. These traces were from observer L.

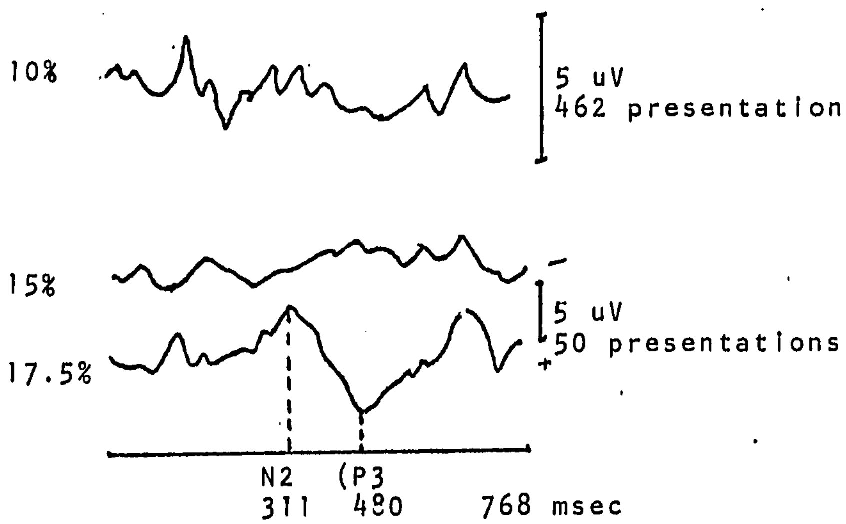
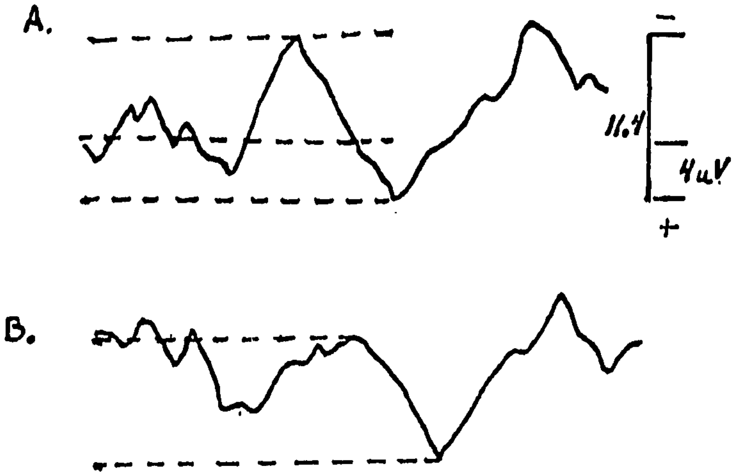

10%
5 uV
462 presentations
15%
17.5%
5 uV
50 presentations
N2
(P3
311
480
768 msec

Figure 6. **A**. An example of a rare trace recorded from P_Z, when the frequent stimulus was 30% contrast and the rare stimulus was 40% contrast. The baseline-to-P3 amplitude was 4 µV versus the N2-P3 peak-to-peak amplitude, which was 11.4 µV. Observer G.

B. An example of a rare trace recorded from P_Z when the frequent stimulus had a contrast of 30% and the rare stimulus had a contrast of 20%. In this instance, N2 had a negative deflection, but was insufficient to cross the baseline. Observer L.


A.
B.
11.4
4uV
-
+

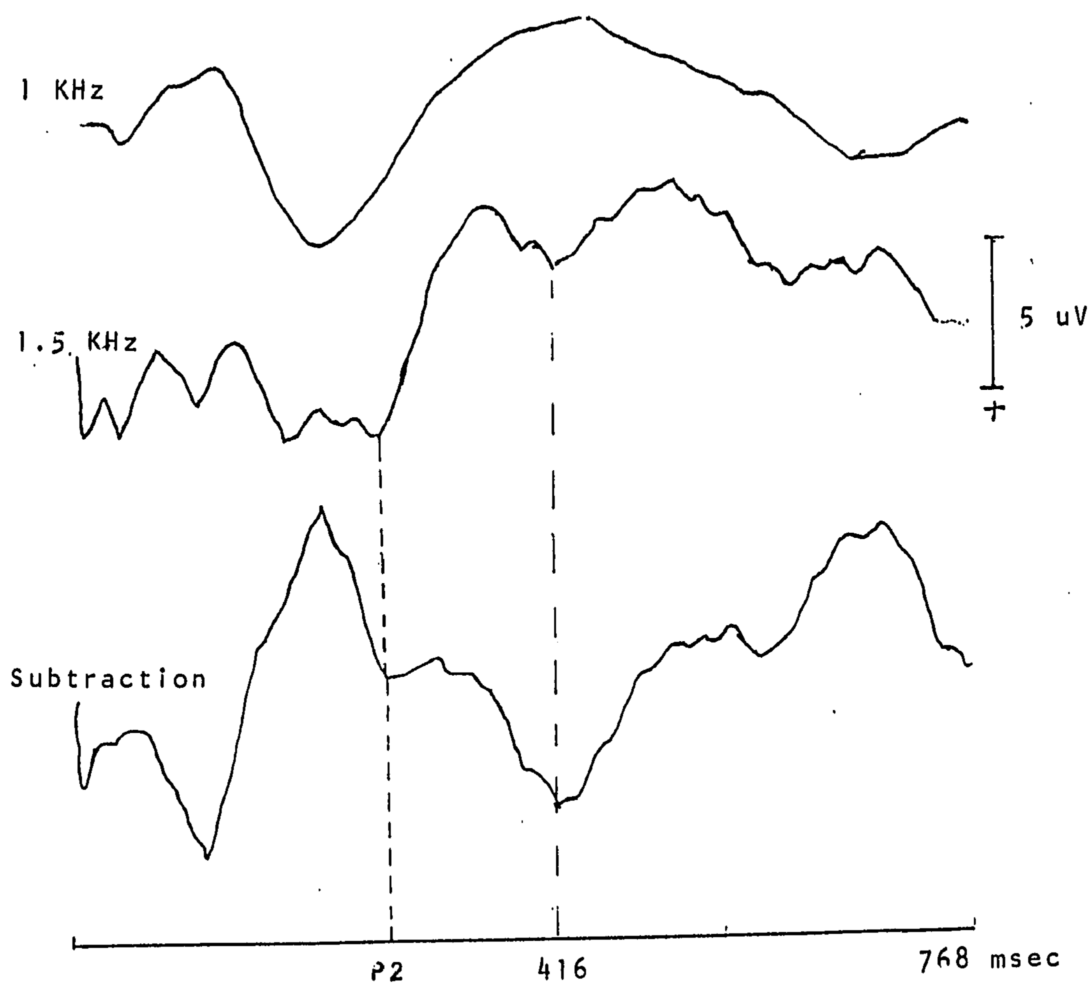
our lab, on several occasions, we observed when testing patients that the subtracted trace would show a P3 when the summated trace would be questionable. Figure 7 shows traces elicited by auditory stimuli and recorded from the Z_{63} electrode referred to linked mastoids. The top trace was to a 1000 Hz tone which was presented randomly 90% of the time. The center trace was to the rare stimulus which was a 1500 Hz tone that had to be counted. This trace shows a small positive deflection at 416 msec; on the other hand, the bottom trace, which is the subtraction confirms the presence of a P3 at 416 msec and also shows a small P2 which resemble those traces seen in Squires, Squires and Hillyard (1975a, p. 272) recorded on high-confidence hit trials. These traces were recorded from a 58 year old female with Parkinson's disease when she had to count the rare tones.

The subtracted waveforms were obtained by dividing the waveforms produced by the frequent stimulus by eight [$F(2^{-3})$] and then subtracting them from the rare waveforms. The rationale for dividing the frequent waveform by 8 before subtracting it from the rare is that it gives the frequent waveform the equivalent of a waveform which consists of 58 presentations. Since the rare is the sum of 50 presentations, this transformation of the frequent waveform is the closest to the rare waveform that the equipment can make.

Figure 7. These traces were elicited by auditory stimuli from a 58 year old female with Parkinson's disease. Tones were presented randomly in an "oddball" paradigm. The top trace is the summation of 462 presentations of a 1000 Hz tone. The middle trace is to a 1500 Hz tone which had to be counted. This middle trace shows a positive deflection at 416 msec that is a questionable P3. The bottom trace, which is the subtraction, confirms the presence of a P3 at the same latency as well as a P2.

The patient gave an accurate count of the number of rare presentations.

AUDITORY



For each observer there were at least 240 waveforms, from 60 conditions. Each condition lasted about 12 minutes. This resulted in at least 12 hours of evoked potential testing of each observer, not including the time spent giving instructions, applying and removing electrodes, changing the stimulus contrast between conditions, and storing the data after each condition.

Data Analysis

Amplitude and latency of the ERPs were compared between the frequent and rare presentations as well as across contrasts and electrode locations.

The difference in contrast between the frequent stimulus and each rare stimulus was converted to $\Delta C/C$ by subtracting the contrast of the rare stimulus from the contrast of the frequent, then dividing the difference by the contrast of the frequent stimulus. This normalization was performed because equal contrast differences between the two stimuli at different frequent contrasts have different ratios. For instance, when the frequent stimulus is 10% and the rare is 5%, 5% is .5 of the frequent; however, when the frequent stimulus is 50% and the rare stimulus is 5%, the rare is only .1 of the contrast of the frequent stimulus. In addition, expressing the results in reference to $\Delta C/C$ permitted the comparison of a standard psychophysical term, as the Weber's ratio, with the ERP results.

The latency of the N2 and the P3 and the N2-P3 peak-to-peak amplitude were plotted as a function of $\Delta C/C$ and as a function of ΔC for each standard contrast for each observer at both electrode locations. This analysis was performed in order to evaluate if latency and/or amplitude would be affected by the magnitude of the contrast difference between the frequent and the rare stimuli. Thirty-six functions for observer G, and 33 functions for observers M and L were obtained; N2 latency, P3 latency and peak-to-peak amplitude as a function of $\Delta C/C$, at the two electrode sites for the six standard contrasts.

The slopes of the functions that described the N2 latency, the P3 latency and the N2-P3 amplitude to the $\Delta C/C$ were subjected to repeated-measures ANOVAs to see if there was an effect of electrode site or the repeated-measure, frequent contrast. The Epsilon-adjustment procedure for repeated measures (df reduced by $E = 1/(K-1)$, K = the number of treatments) described by Jennings and Wood (1976) was used.

Pearson Product-Moment correlation coefficients were computed. The Pearson Product-Moment correlation coefficient was used as an index of dependence rather than its more conventional statistical application since $\Delta C/C$ is not independent. The confidence limits for the correlation coefficients were set at Alpha = 0.05, two-tailed test. The correlation coefficients were transformed by Fisher's $\underline{z}$ ($\underline{z} = 0.5 \ln((1+\underline{r})/(1-\underline{r}))$ to approximate the normal distribution (Zar, 1984), and the confidence limits were computed on the Fisher's z-transformations with the following formula: reject H_0 when $z/\sqrt{1/(N-3)} \geq 1.96$.

Means and standard deviations were computed within observers for latency of the N2 and P3 and the N2-P3 peak-to-peak amplitude for all the rare traces at both electrode sites.

In addition, the means and standard deviations were computed within observers for latency of the N2 and P3 and the N2-P3 peak-to-peak amplitude[6] for all the subtracted traces at both electrode sites and compared with the summated traces.

[6] The amplitudes derived from the subtracted traces do not represent true amplitude measures, they are the voltage difference between the frequent and the rare traces.

Chapter 5. Results of the Electrophysiological Study

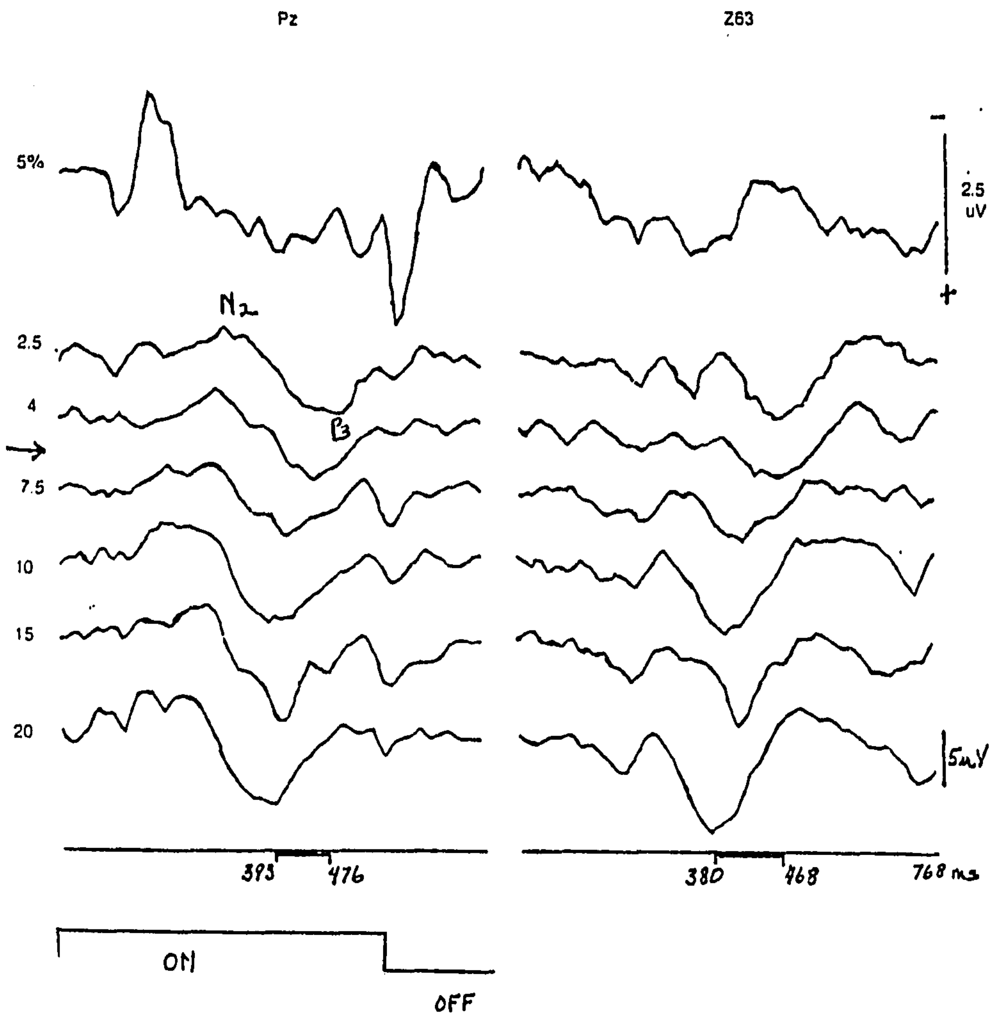
ERPs which resemble those seen in the literature were obtained from all three observers. Figure 8 is an example of the traces obtained from one observer (M). The top traces were obtained to the presentation of the frequent stimulus which had 5% contrast. This trace is the summation of 462 stimulus presentations. The traces on the left were recorded from the P_Z electrode site and on the right from the Z_{63} electrode. The top, left, trace clearly shows the evoked potential to the onset and to the offset of the stimulus, but does not show a P3 response. The ERPs below the frequent waveforms are to the rare stimuli and they are the summation of 50 stimulus presentations; they are different in shape from the frequent trace, with evident N2s and P3s. As seen in these traces, the latency of the N2 and P3 tend to increase while the amplitude tends to decrease as the difference in contrast between the stimuli becomes smaller. At all standard contrasts and at both electrode sites, G had evident N2s for the frequent as well as the rare stimuli; this was less evident in L's traces and N2 was absent in M's traces. Additional waveforms, from each subject at both electrode sites, are shown in Appendix B.

Latency of the N2 and P3 and the N2-P3 peak-to-peak amplitude were plotted as a function of $\Delta C/C$ and regression lines were fitted

Figure 8. An example of the traces obtained from one observer (M) when the frequent contrast was 5%. The top traces are to the frequent stimulus, and is a summation of 462 stimulus presentations. The traces on the left were recorded from the P_Z electrode site and on the right from the Z_{63} electrode site, both were referred to linked mastoids. The stimulus-locked "on" and "off" responses are apparent in the frequent trace recorded from the P_Z electrode site.

The remaining traces are to the rare stimuli; each trace is the sum of 50 stimulus presentations. The latency difference between the earliest and the most delayed P3 is indicated under the traces. The numbers to the left of the traces indicate the contrast of the pattern, not the contrast difference between the two patterns. The arrow between the rare traces of 4 and 7.5 indicates where in the sequence of the rare traces the frequent contrast would be.

The remaining traces are seen in Appendix B.


Pz
Z63
5%
2.5
4
7.5
10
15
20
N2
P3
2.5 uV
5uV
393
476
380
468
768 ms
ON
OFF

for each person at each standard contrast. Figures 9 through 17 show these plots. Sixty-seven of the 68 regression lines fitted for latency versus the ΔC/C had negative slopes, indicating that as the difference in contrast between the rare and the frequent patterns increased, the latency of the N2 and P3 decreased. Regression lines that were fitted to the peak-to-peak amplitude versus ΔC/C were positive for 28 of 34 plots indicating that amplitude increased as the ΔC/C increased. Of the remaining six analyses, five were negative for observer L and one for observer G; all of the amplitude by ΔC/C regression lines obtained from observer M were positive.

The steepest slopes of the regression lines that were fitted to the N2 latency, the P3 latency and the amplitude versus the ΔC/C were for the frequent contrasts of 40% and 50%. Those with the least inclinations described the functions for the frequent contrasts of 5% and 10%. Figures 18, 19 and 20 show the inclinations of the slopes of the regression lines that were fitted to the N2 latency, the P3 latency and the N2-P3 amplitude versus the ΔC/C as a function of the frequent contrast (The data for Figures 18, 19 and 20 are the slopes seen in Figures 9 - 17). The slopes increased in steepness as the frequent contrast increased from 5% to 30%; the linearity seems to break down at 40% contrast. Frequent contrast had a significant effect on the slopes plotted for P3 latency as a function of the ΔC/C;

Text continues on page 94.

Figure 9. N2 latency plotted as a function of $\Delta C/C$.

The slopes of the functions for the frequent contrasts are:

5% -15; 10% -34; 20% -17.4; 30% abs; 40% -37; 50% -102

Each symbol represents a different frequent contrast. The symbol for the frequent contrast that each regression line describes is at the intercept.

These plots represent the responses from observer M that were recorded at the P_Z electrode site.

This observer was not tested at the P_Z electrode site for 30% frequent contrast.

Note, the regression lines and intercepts for the frequent contrasts of 5% and 20% are almost identical.

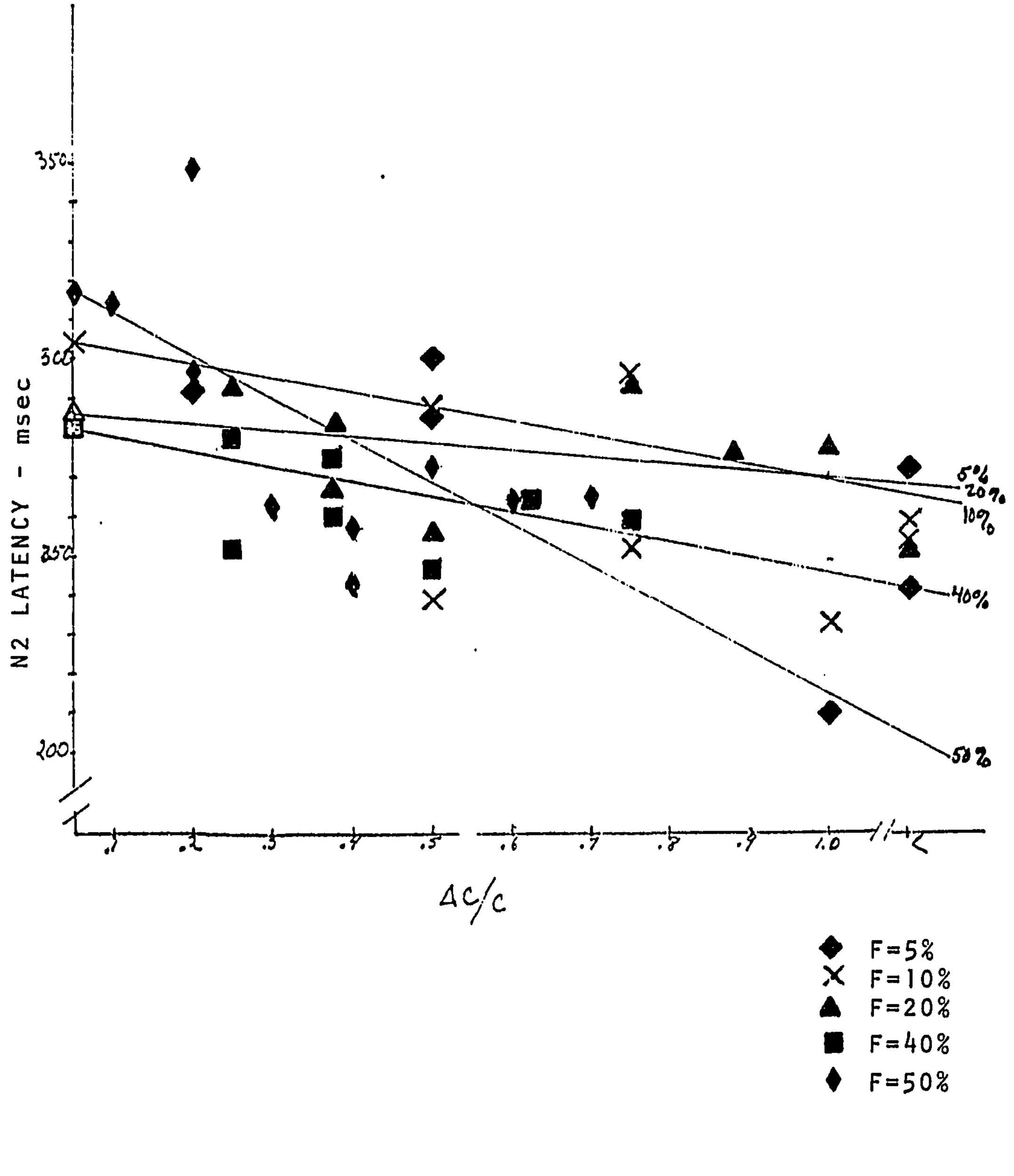

N2 LATENCY - msec
350
300
250
200
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
2
ΔC/C
5%
20%
10%
40%
50%
F=5%
F=10%
F=20%
F=40%
F=50%

Figure 10. P3 latency plotted as a function of $\Delta C/C$.

The slopes of the functions for the frequent contrasts are:

5% -26; 10% -42; 20% -76; 30% abs; 40% -50; 50% -137

Each symbol represents a different frequent contrast. The symbol for the frequent contrast that each regression line describes is at the intercept.

These plots represent the responses from observer M that were recorded at the P_Z electrode site. This observer was not tested at the P_Z electrode site for 30% frequent contrast.

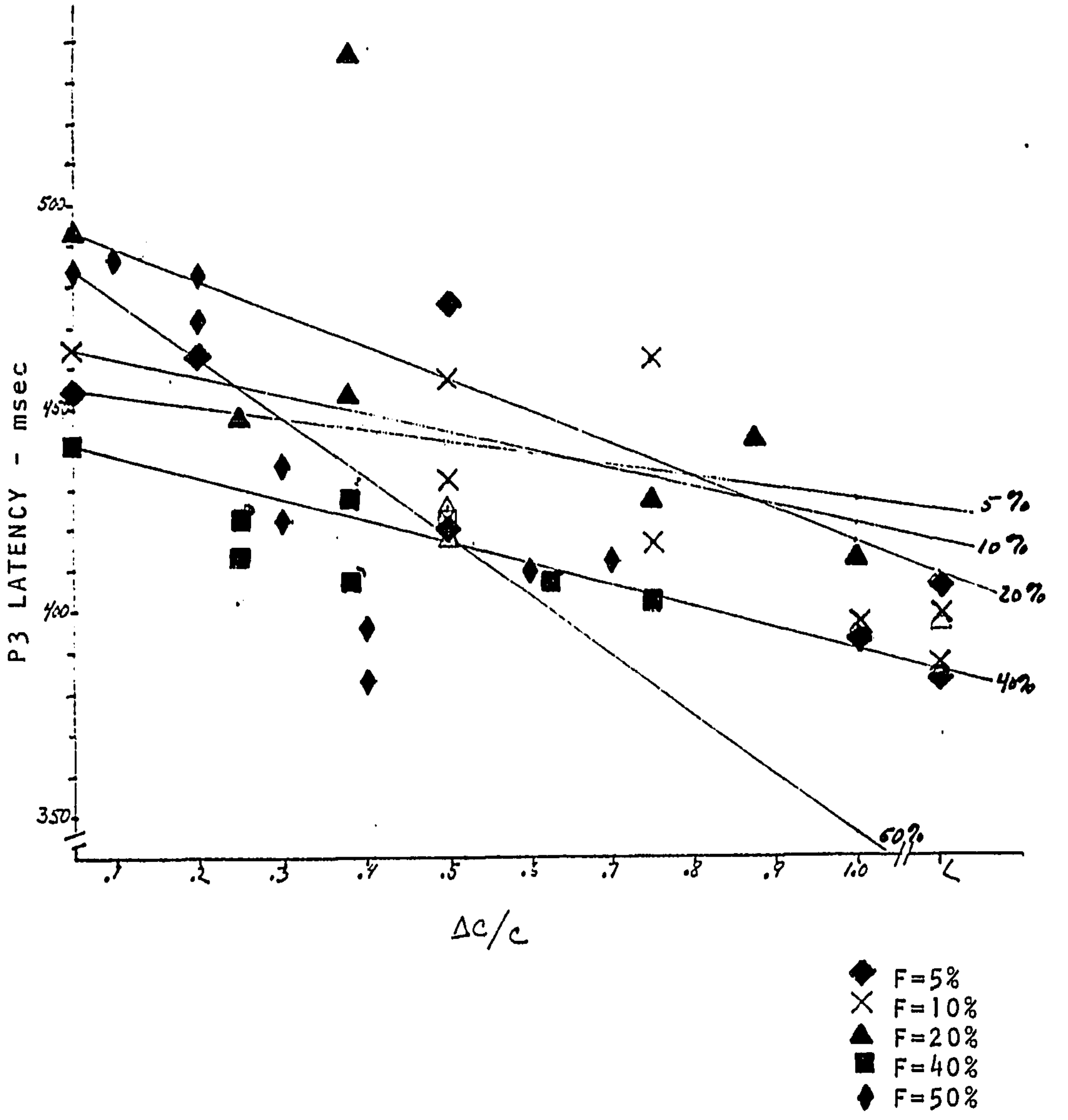

P3 LATENCY - msec
500
450
400
350
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
L
Δc/c
5%
10%
20%
40%
60%
F=5%
F=10%
F=20%
F=40%
F=50%

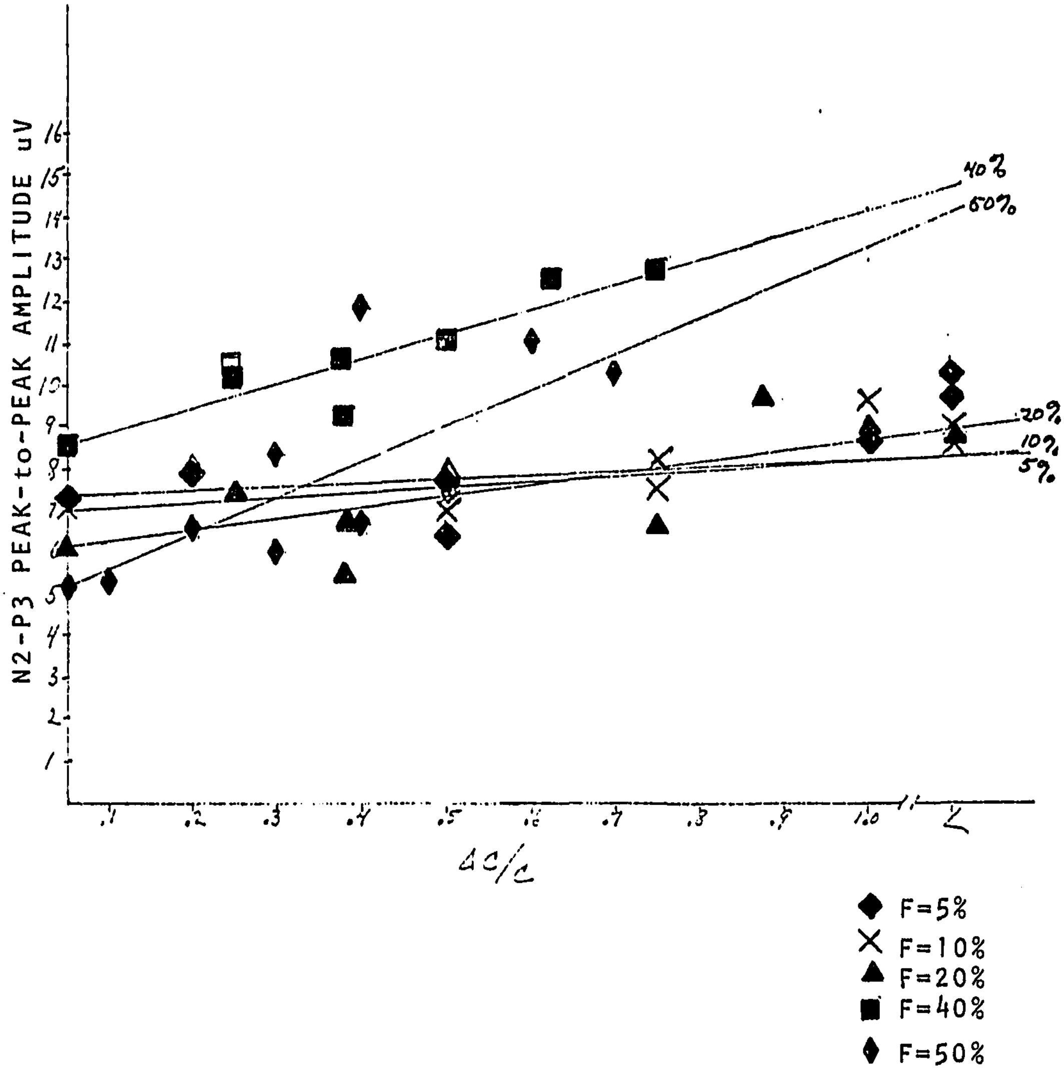
Figure 11. N2-P3 peak-to-peak amplitude plotted as a function of ΔC/C.

The slopes of the functions for the frequent contrasts are:

5% 1; 10% 1.2; 20% 2.6; 30% abs; 40% 5.7; 50% 8

Each symbol represents a different frequent contrast. The symbol for the frequent contrast that each regression line describes is at the intercept.

These plots represent the responses from observer M that were recorded at the P_Z electrode site.



N2-P3 PEAK-to-PEAK AMPLITUDE uV
40%
50%
20%
10%
5%
ΔC/C
F=5%
F=10%
F=20%
F=40%
F=50%

Figure 12. N2 latency plotted as a function of $\Delta C/C$.

The slopes of the functions for the frequent contrasts are:

5% -23; 10% -5; 20% -42; 30% -15; 40% -43; 50% -60

Each symbol represents a different frequent contrast. The symbol for the frequent contrast that each regression line describes is at the intercept.

These plots represent the responses from observer G recorded at the P_Z electrode site.

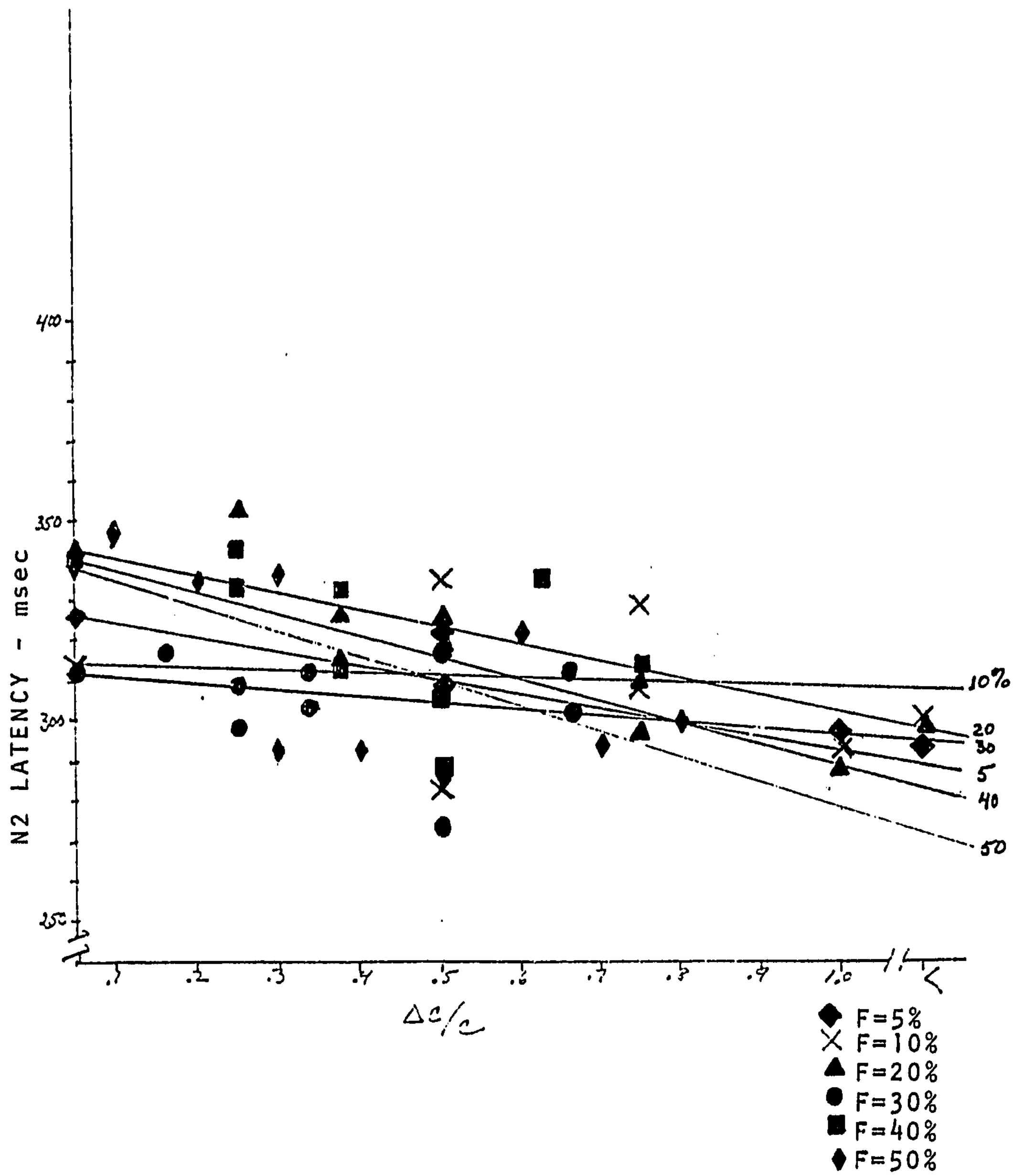

N2 LATENCY - msec
400
350
300
250
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
Δc/c
10%
20
30
5
40
50
F=5%
F=10%
F=20%
F=30%
F=40%
F=50%

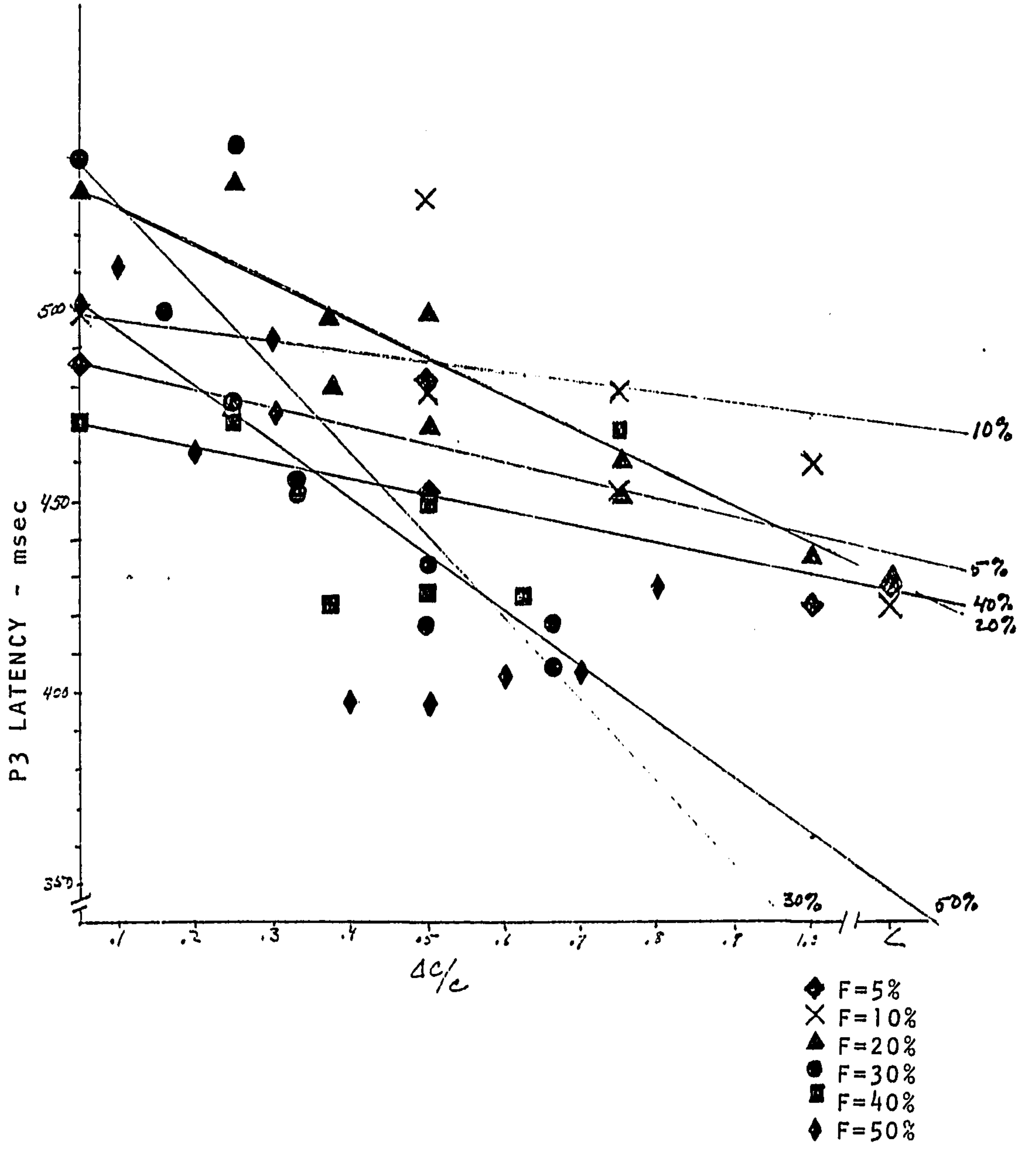
Figure 13. P3 latency plotted as a function of $\Delta C/C$.

The slopes of the functions for the frequent contrasts are:

5% -45; 10% -27; 20% -93; 30% -204; 40% -41; 50% -141

Each symbol represents a different frequent contrast. The symbol for the frequent contrast that each regression line describes is at the intercept.

These plots represent the responses from observer G recorded at the P_Z electrode site.



P3 LATENCY - msec
500
450
400
350
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
2
ΔC/C
10%
5%
40%
20%
30%
50%
F=5%
F=10%
F=20%
F=30%
F=40%
F=50%

Figure 14. N2-P3 peak-to-peak amplitude plotted as a function of $\Delta C/C$.

The slopes of the functions for the frequent contrasts are:

5% -.25; 10% .7; 20% 2.8; 30% 9.7; 40% 6.6; 50% 1

Each symbol represents a different frequent contrast. The symbol for the frequent contrast that each regression line describes is at the intercept.

These plots represent the responses from observer G recorded at the P_Z electrode site.

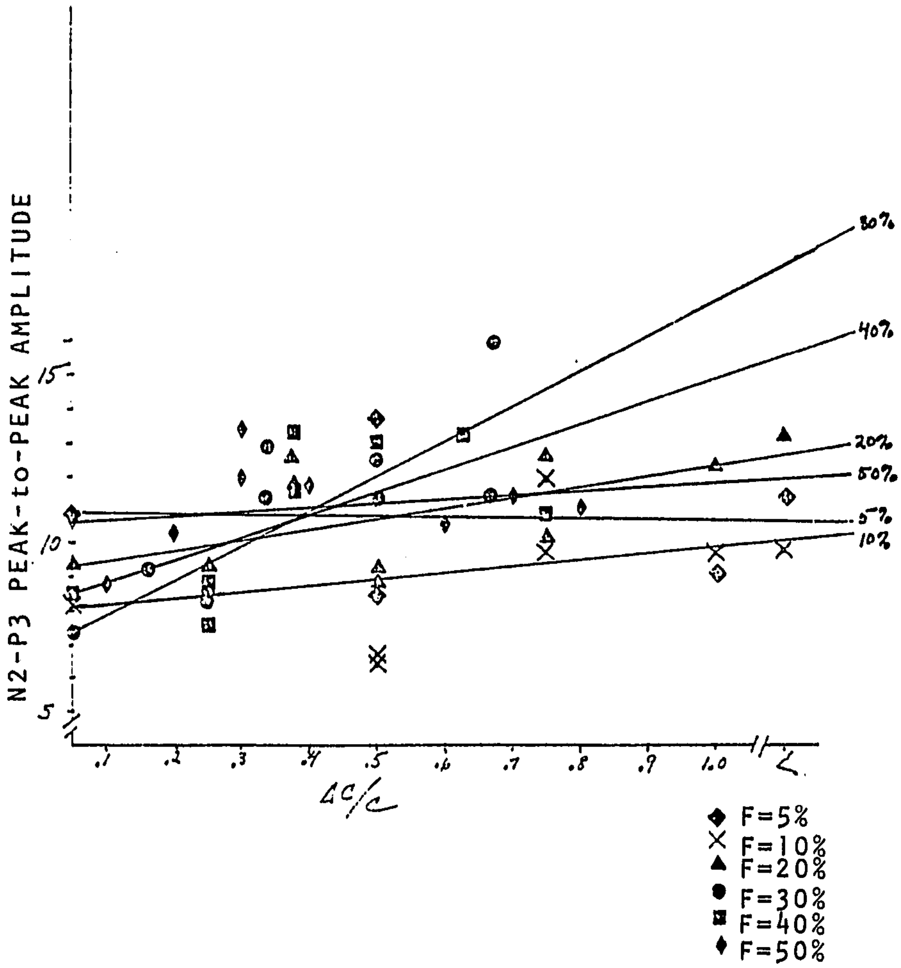

N2-P3 PEAK-to-PEAK AMPLITUDE
15
10
5
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
2
ΔC/C
30%
40%
20%
50%
5%
10%
F=5%
F=10%
F=20%
F=30%
F=40%
F=50%

Figure 15. N2 latency plotted as a function of $\Delta C/C$.

The slopes of the functions for the frequent contrasts are:

5% -34; 10% -2.2; 20% abs; 30% -80; 40% -236; 50% -121

Each symbol represents a different frequent contrast. The symbol for the frequent contrast that each regression line describes is at the intercept.

These plots represent the responses from observer L recorded at the P_Z electrode site.

Note: at 5% frequent contrast, all of the responses are at $\Delta C/C \geq 1.0$.

This observer was not tested at the P_Z electrode site for 20% frequent contrast.

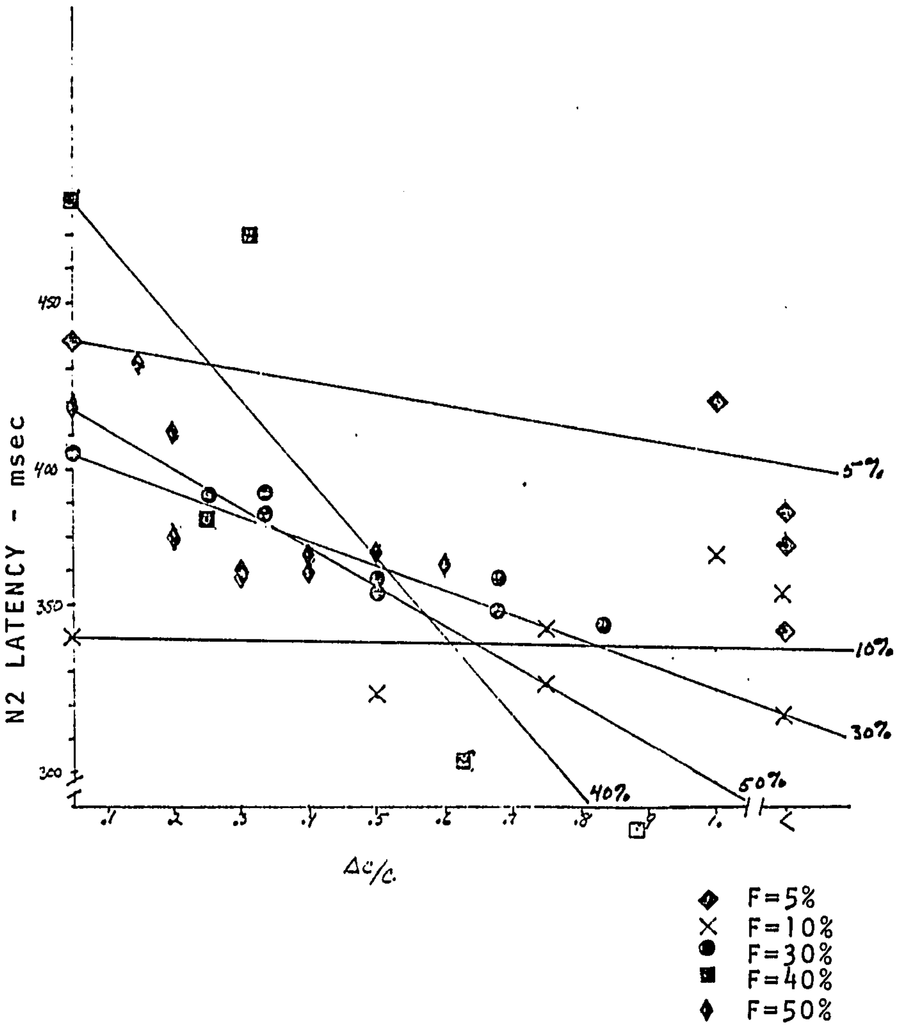

N2 LATENCY - msec
450
400
350
300
5%
10%
30%
40%
50%
.1
.2
.3
.4
.5
.6
.7
.8
1.
Δc/c.
F=5%
F=10%
F=30%
F=40%
F=50%

Figure 16. P3 latency plotted as a function of $\Delta C/C$.

The slopes of the functions for the frequent contrasts are:

5% -16; 10% -49; 20% abs; 30% -109; 40% -66; 50% -144

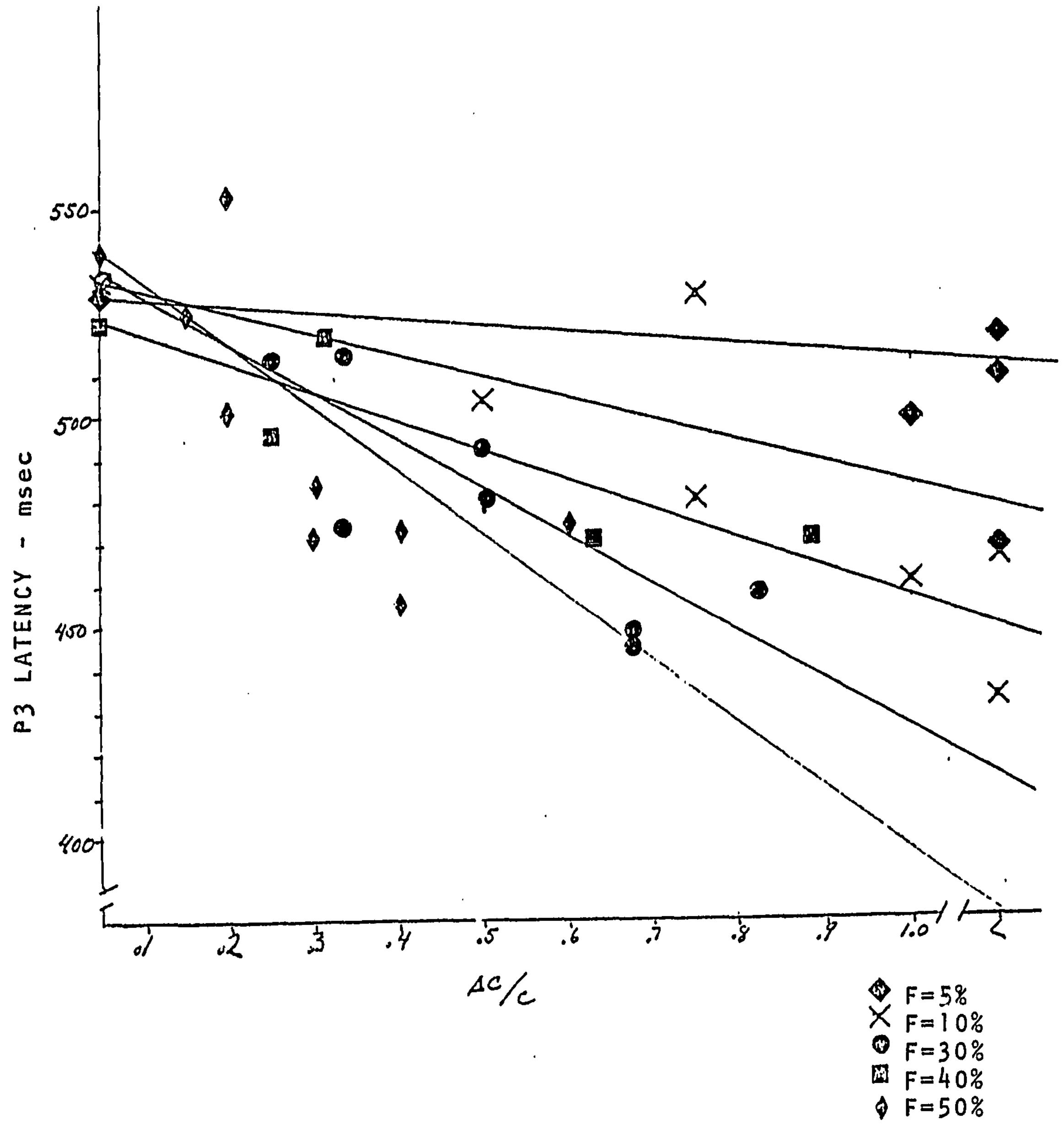
Each symbol represents a different frequent contrast. The symbol for the frequent contrast that each regression line describes is at the intercept.

These plots represent the responses from observer L recorded at the P_Z electrode site.

Note: at 5% frequent contrast, all of the responses are at $\Delta C/C \geq 1.0$.

This observer was not tested at the P_Z electrode site for 20% frequent contrast.

The symbols for the regression lines are at the beginning and the end of each line.



550
500
450
400
P3 LATENCY - msec
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
2
ΔC/C
F=5%
F=10%
F=30%
F=40%
F=50%

Figure 17. N2-P3 peak-to-peak amplitude plotted as a function of $\Delta C/C$.

The slopes of the functions for the frequent contrasts are:

5% 1.4; 10% .78; 20% abs; 30% 3; 40% -1.9; 50% 7.9

Each symbol represents a different frequent contrast. The symbol for the frequent contrast that each regression line describes is at the intercept.

These plots represent the responses from observer L recorded at the P_Z electrode site.

Note: at 5% frequent contrast, all of the responses are at $\Delta C/C \geq 1.0$.

This observer was not tested at the P_Z electrode site for 20% frequent contrast.

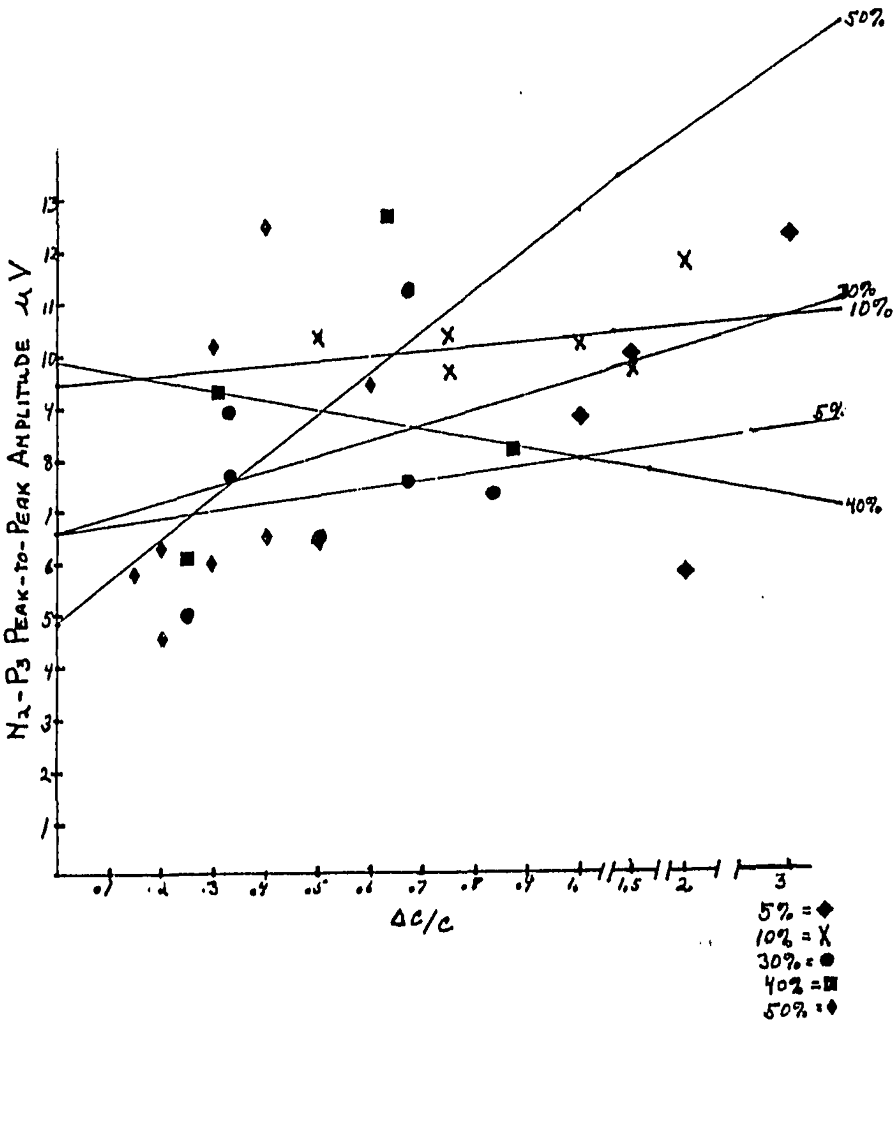

50%
30%
10%
5%
40%
N2-P3 Peak-to-Peak Amplitude μV
13
12
11
10
9
8
7
6
5
4
3
2
1
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.
1.5
2.
3
ΔC/C
5% = ◆
10% = X
30% = ●
40% = ■
50% = ♦

Figure 18. The slopes of the functions that were derived when N2 latency was plotted as a function of the $\Delta C/C$ for each frequent contrast. The slopes increased in steepness as the frequent contrast increased. The solid line describes the slopes obtained at the P_z electrode site, and the dashed line at the Z_{63} electrode site. The data points for the P_z electrode site are the means of the slopes seen in Figures 9, 12 and 15. The slopes of the functions are on the ordinate and the frequent contrast is on the abscissa.

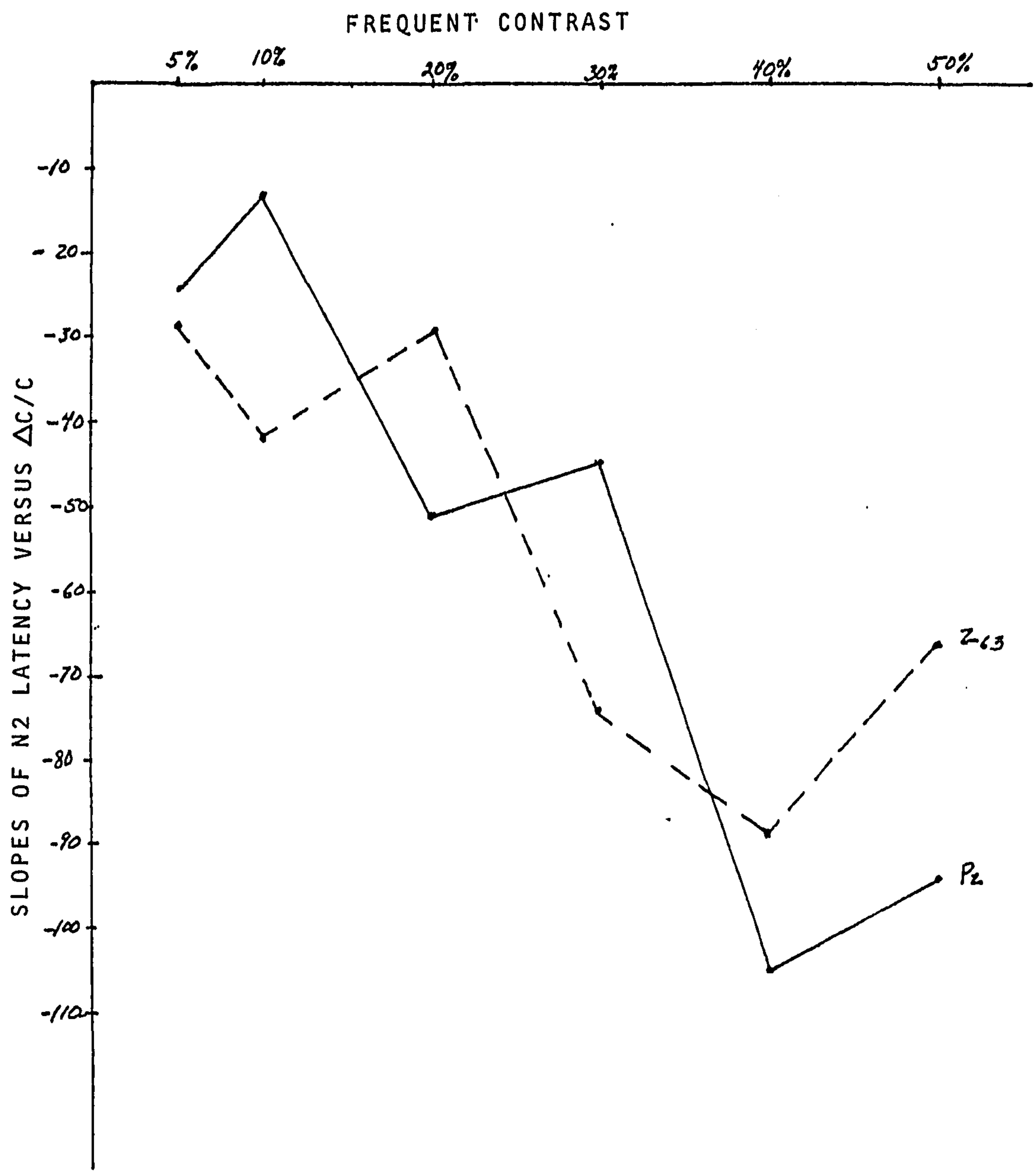

FREQUENT CONTRAST
5%
10%
20%
30%
40%
50%
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
SLOPES OF N2 LATENCY VERSUS ΔC/C
Pz

Figure 19. The slopes of the functions that were derived when P3 latency was plotted as a function of the ΔC/C for each frequent contrast. The slopes increased in steepness as the frequent contrast increased. The solid line describes the slopes obtained at the P_Z electrode site and the dashed line at the Z_{63} electrode site. The data points for the P_Z electrode site are the means of the slopes seen in Figures 10, 13 and 16. The slopes of the functions are on the ordinate and the frequent contrast is on the abscissa.

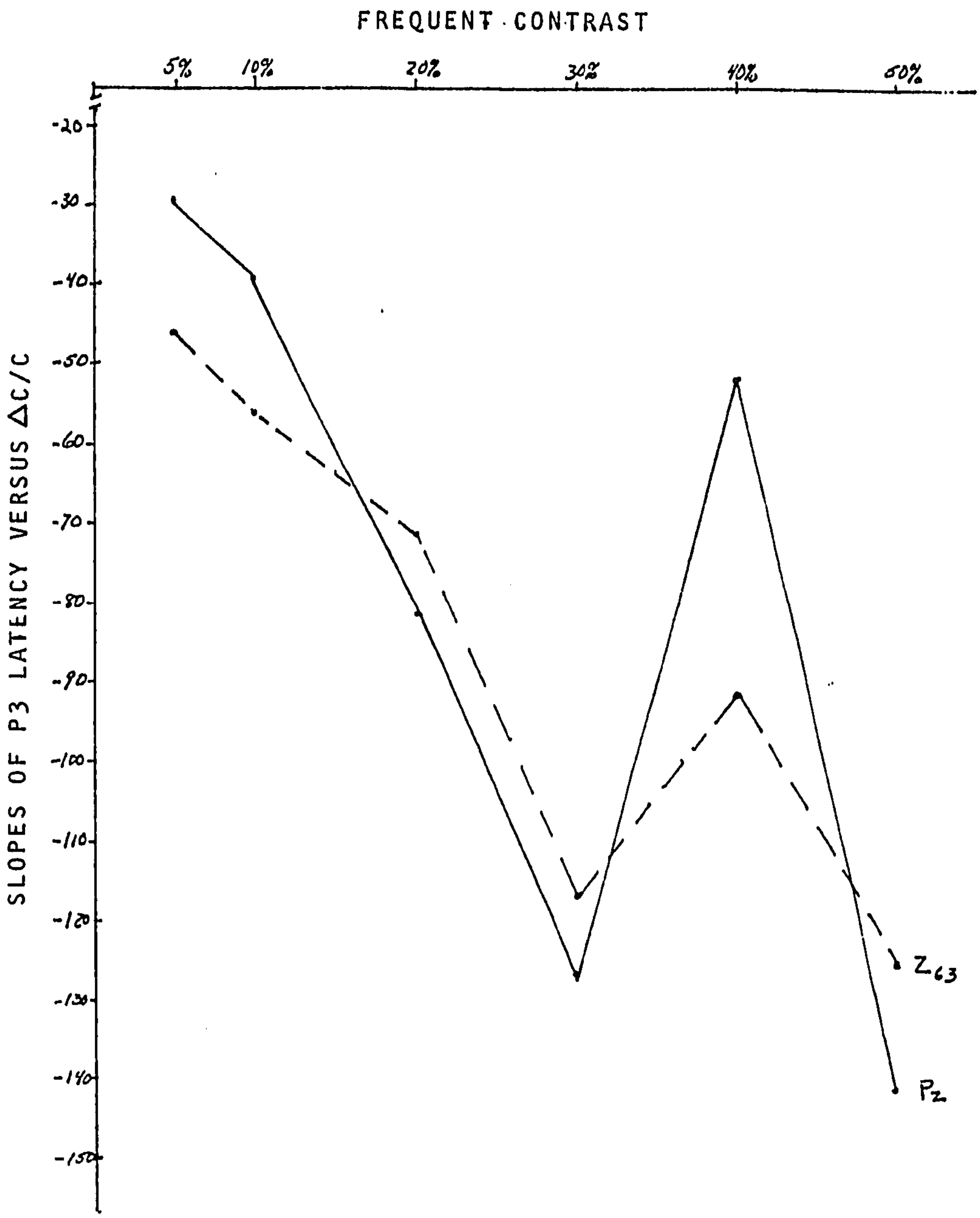
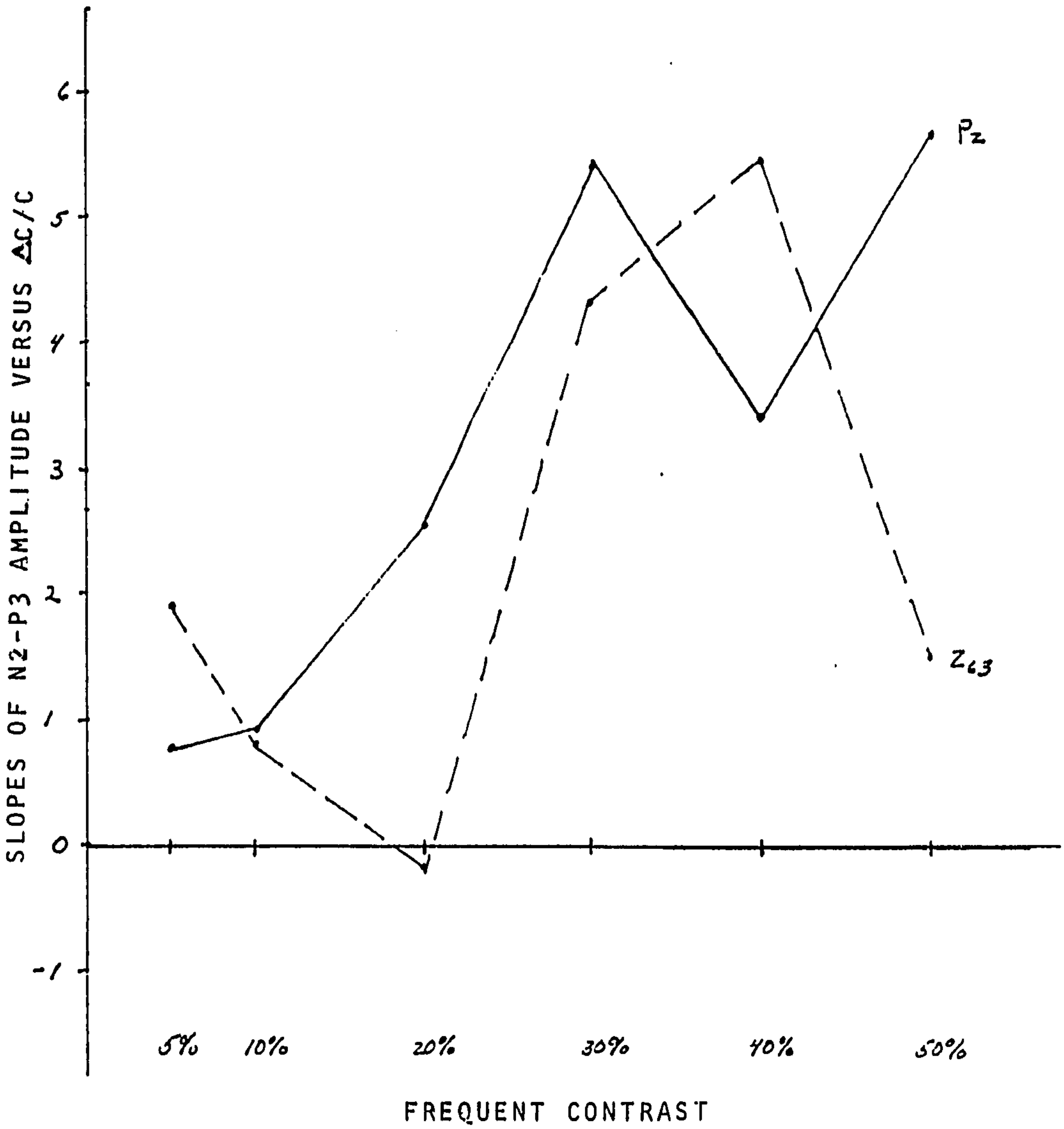

FREQUENT CONTRAST
5%
10%
20%
30%
40%
60%
SLOPES OF P3 LATENCY VERSUS ΔC/C
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
-120
-130
-140
-150
Z63
Pz

Figure 20. The slopes of the functions that were derived when N2-P3 peak-to-peak amplitude was plotted as a function of the $\Delta C/C$ for each frequent contrast. The same tendency is apparent on this figure, as was seen for the latency measures, i.e., that the slopes increased in steepness as the frequent contrast increased. The solid line describes the slopes obtained at the P_z electrode site and the dashed line at the Z_{63} electrode site. The data points for the P_z electrode site are the means of the slopes seen in Figures 11, 14 and 17. The slopes of the functions are on the ordinate and the frequent contrast is on the abscissa.


SLOPES OF N2-P3 AMPLITUDE VERSUS ΔC/C
6
5
4
3
2
1
0
-1
Pz
Z63
5%
10%
20%
30%
40%
50%
FREQUENT CONTRAST

$\underline{F}(5,20) = 4.745$, $\underline{p} = .0051$. The slopes plotted for amplitude as a function of the ΔC/C; $\underline{F}(5,20) = 1.966$, $\underline{p} = .128$, and the slopes plotted for N2 latency versus ΔC/C did not reach significance; $\underline{F}(5,20) = 2.396$, $\underline{p} = .074$. There was no difference between the electrode sites (Table 2).

These results indicated: 1) ERPs were elicited by the rare stimulus.[7] 2) The latency of the N2 and the P3 decreased and the N2-P3 amplitude increased as the ΔC increased. 3) There was no difference between electrode sites for these measures; and 4) Frequent contrast had a significant effect on the slopes of the regression lines that were plotted as a function of the ΔC/C for P3 latency; steeper slopes were obtained for higher frequent contrasts.

Correlation Coefficients

Correlation coefficients were computed in order to show an index of dependence of the latency and amplitude on the ΔC/C. The correlation coefficients between latency and ΔC/C were negative;

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[7] Six different contrasts were used for the frequent stimulus; they were compared with stimuli that varied below and above the frequent contrast. Therefore, each frequent contrast was also a rare contrast for a different frequent contrast. For instance, when the frequent was 10%, it was compared with contrasts that were used as the frequent stimulus in other recording sessions such as 5%, 20% and 30% (Appendix B). In each instance, reliable and reproducable P3s were recorded to the rare stimulus. This demonstrates that the P3 can be elicited when an irrelevant stimulus is made relevant.

Table 2

Repeated-Measures ANOVAs Which Examined the Effect of Electrode and Frequent Contrast on the Slopes of the Functions that Described the N2 Latency Versus the ΔC/C (Top), the P3 Latency Versus the ΔC/C (Middle), and the Peak-to-Peak Amplitude Versus the ΔC/C

Source	SS	df	MS	F	p
Slopes of N2 Latency versus ΔC/C					
(A) Electrode	3.934	1	3.934	.001	.9783
Error	18830.564	4	4707.641		
(B) Fr. Contrast	25181.061	5	5036.212	2.396	.074
A x B	4812.935	5	962.587	.458	.8027
Error	42043.376	20	2102.169		
			Epsilon Correction .2		
Slopes of P3 Latency versus ΔC/C					
(A) Electrode	360.367	1	360.367	.172	.6995
Error	8371.712	4	2092.928		
(B) Fr. Contrast	44918.479	5	8983.696	4.745	.0051
A x B	3436.001	5	687.2	.363	.8678
Error	37868.028	20	1893.401		
			Epsilon Correction .2		
Slopes of the Peak-to-Peak Amplitude versus ΔC/C					
(A) Electrode	11.594	1	11.594	.294	.6165
Error	157.797	4	39.449		
(B) Fr. Contrast	79.186	5	15.837	1.966	.1282
A x B	46.112	5	9.222	1.145	.3699
Error	161.146	20	8.057		
			Epsilon Correction .2		

while the correlation coefficients tended to be positive when amplitude and ΔC/C were examined. Tables 3, 4, and 5 show the Pearson Product-Moment correlation coefficients which examined the relationships between the latency and the ΔC/C and the relationships between the amplitude and the ΔC/C at both electrode sites. The correlation coefficients that fell within the critical region for rejecting the null hypothesis are indicated on the Tables by asterisks (28% of the correlations computed fell within the critical regions, $p < .05$, and 55% of these were for P3 latency). The means of the correlations between P3 latency and the ΔC/C were higher than those between N2 latency or amplitude and ΔC/C (Table 6). There was no difference between the electrode sites for P3 latency (Figure 21).

ERP-JND

The minimum ΔC/C that the observers required to produce waveforms with evident P3s were considered the event-related potential - just noticeable difference (ERP-JND). To insure that a P3 was not elicited with a smaller ΔC, when a trace appeared to be missing a P3, the deflections in the waveform that occurred within the 350-550 msec latency range were compared against the maximum excursion within the first 10 msec of the epoch. If a deflection within the P3 latency range exceeded the maximum excursion within the first 10 msec of the epoch, that deflection would have been

Text continues on page 103

Table 3

Pearson Product-Moment Correlation Coefficient Showing the Relationships of the Latency and Amplitude to the ΔC/C for Observer M

	FREQUENT CONTRAST					
	5%	10%	20%	30%	40%	50%
P_Z						
N2	-.47	-.48	-.39		-.44	-.61
P3	-.74	-.78*	-.63		-.61	-.72*
AMP	+.81	+.69	+.67		+.89*	+.68*
Z_{63}						
N2	-.78	-.56	-.79*	-.71	-.64	-.19
P3	-.79	-.81*	-.81*	-.34	-.55	-.58
AMP	+.82*	+.35	+.32	+.26	+.64	.00

*These correlation coefficients fell within the critical region, i.e., > 95% confidence limits.

For these data a linear regression model was used to describe the dependent variables as a linear function of the ΔC/C.

Table 4

Pearson Product-Moment Correlation Coefficients Showing the Relationships of the Latency and Amplitude to the ΔC/C for Observer G

	FREQUENT CONTRAST					
	5%	10%	20%	30%	40%	50%
P_Z						
N2	-.85	-.24	-.73*	-.20	-.41	-.62
P3	-.79	-.75	-.91*	-.86*	-.29	-.74*
AMP	-.05	+.36	+.53	+.74*	+.54	+.18
Z_{63}						
N2	-.70	-.44	-.82*	-.68*	-.51	-.66
P3	-.73	-.82*	-.92*	-.87*	-.70	-.93*
AMP	+.72	+.92*	+.57	+.74*	+.72*	+.39

* These correlation coefficients fell within the critical region, i.e., > 95% confidence limits.

For these data a linear regression model was used to describe the dependent variables as a linear function of the ΔC/C.

Table 5

Pearson Product-Moment Correlation Coefficients Showing the Relationships of the Latency and Amplitude to the ΔC/C for Observer L

		FREQUENT CONTRAST					
		5%	10%	20%	30%	40%	50%
P_Z							
	N_2	-.88	-.07		-.91*	-.82	-.68
	P_3	-.63	-.82*		-.82*	-.81	-.70
	AMP	+.44	+.57		+.30	-.21	+.46
Z_{63}							
	N_2	-.82	-.88*	+.82	-.12	-.57	-.66
	P_3	-.73	-.82*	-.04	-.80*	-.70	-.81*
	AMP	+.25	-.13	-.49	-.51	+.09	-.01

* These correlation coefficients fell within the critical region, i.e., > 95% confidence limits.

For these data a linear regression model was used to describe the dependent variables as a linear function of the ΔC/C.

Table 6

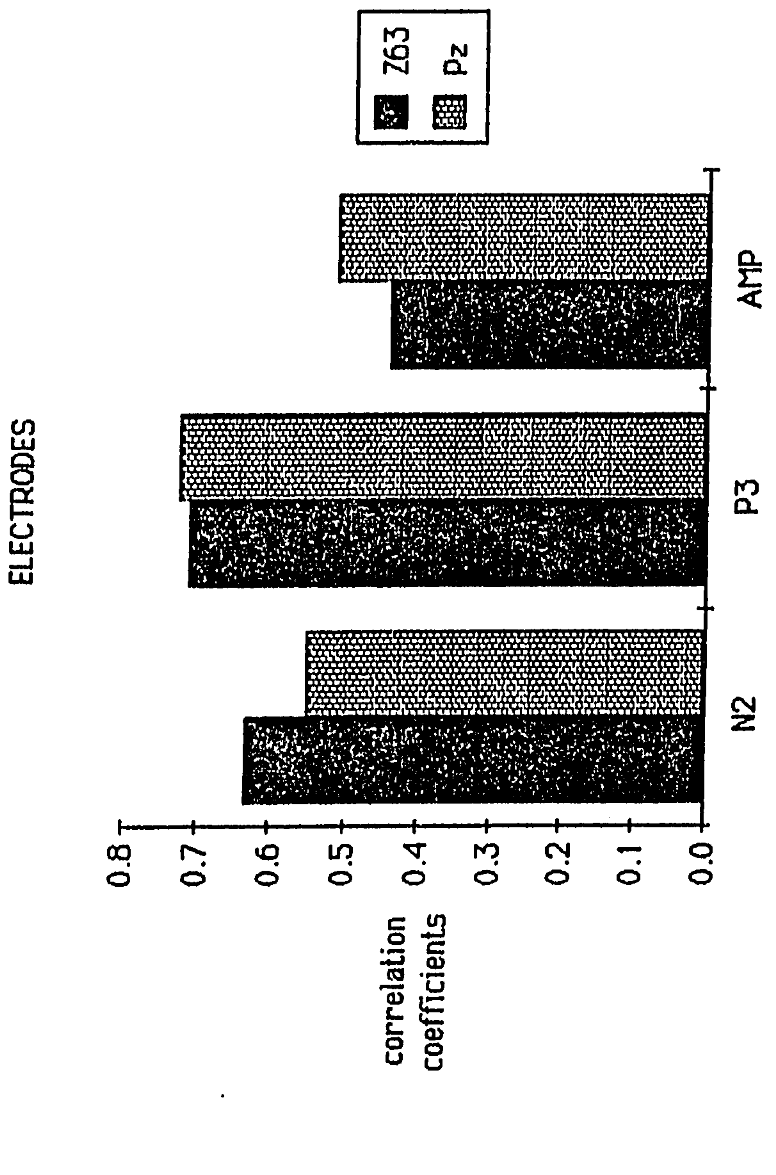
The Means and the Standard Deviations of the Correlation Coefficients Comparing the Latency and Amplitude to the ΔC/C, Combined Across Standard Contrasts

		OBSERVER			
		M	G	L	M
P_z					
	N2	.478 ±.082	.508 ±.266	.672 ±.348	.5527
	P3	.696 ±.073	.723 ±.222	.756 ±.087*	.725
	AMP	.748 ±.098*	.400 ±.255	.396 ±.142	.5147
Z_{63}					
	N2	.612 ±.224	.635 ±.138	.645 ±.282	.6307
	P3	.647 ±.19	.828 ±.097*	.65 ±.303	.7083
	AMP	.398 ±.29	.677 ±.179	.247 ±.211	.4407

Table 6. The means of the correlation coefficients seen on Tables 3 for M, 4 for G, and 5 for L.

*The highest correlation coefficients obtained by each observer.

Figure 21. The means of the correlation coefficients showing the relationships between the latency and amplitude to the $\Delta C/C$ between the electrode sites.


ELECTRODES
correlation coefficients
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
N2
P3
AMP
Z63
Pz

considered a P3. In each case, when a P3 was not visible in the waveform, the observer gave an incorrect count of the number of rare presentations. The subtracted traces were also inspected, and in each case the subtracted traces confirmed the summated traces.

The frequent contrast did show an effect on the ERP-JND. The ERP-JNDs decreased as the standard contrast increased (Table 7). Figure 22 shows that an inverse relationship existed between the ERP-JND and frequent contrast; the slopes of the regression lines were, for observer M = -.0045, for G = -.006, and for L = -.015; while the intercepts were .36, .408 and .807, respectively. Note that observer L had the steepest slope, this occurred because of the large ERP-JND at 5% frequent contrast. It appears that a Weber's law, i.e., that $\Delta C/C$ = constant (K), does not exactly fit these data.

Neither do equal ΔCs, irrespective of the level of the frequent contrast, yield equal ERP-JNDs. If we express the ERP-JND in reference to the just noticeable contrast difference (ΔC) instead of $\Delta C/C$, it is clear that the minimum absolute difference between the frequent and the rare contrasts required to elicit a P3 did not remain constant across frequent contrast.

Smaller ERP-JNDs were required for an observer to produce a P3 when the contrast of the rare stimulus was below the frequent

Continued on page 107.

Table 7

The ERP-JND and ΔC that Produced Waveforms with Evident P3s

	OBSERVER						
	M		G		L		M (ΔC)
FREQUENT CONTRAST	ERP-JND	(ΔC)	ERP-JND	(ΔC)	ERP-JND	(ΔC)	
5%	.2	(1%)	.5	(2.5%)	1.	(5%)	2.8%
10%	.5	(5%)	.25	(2.5%)*	.5	(5%)	4.2%
20%	.25	(5%)	.25	(5%)	.375	(7.5%)	5.8%
30%	.167	(5%)	.167	(5%)	.25	(7.5%)**	5.8%
40%	.25	(10%)	.25	(10%)	.25	(10%)	10%
50%	.1	(5%)	.1	(5%)	.15	(7.5%)	5.8%

*P3 evident at the Z_{63} electrode only

**P3 evident at the P_z electrode only

(ΔC) = The absolute contrast difference between the frequent and the rare contrasts.

Figure 22. Regression lines which show the relationship between the ERP-JND and the frequent contrasts obtained by the three observers.

Note: The data points for M and G overlap at frequent contrasts 20%, 30%, 40% and 50%.

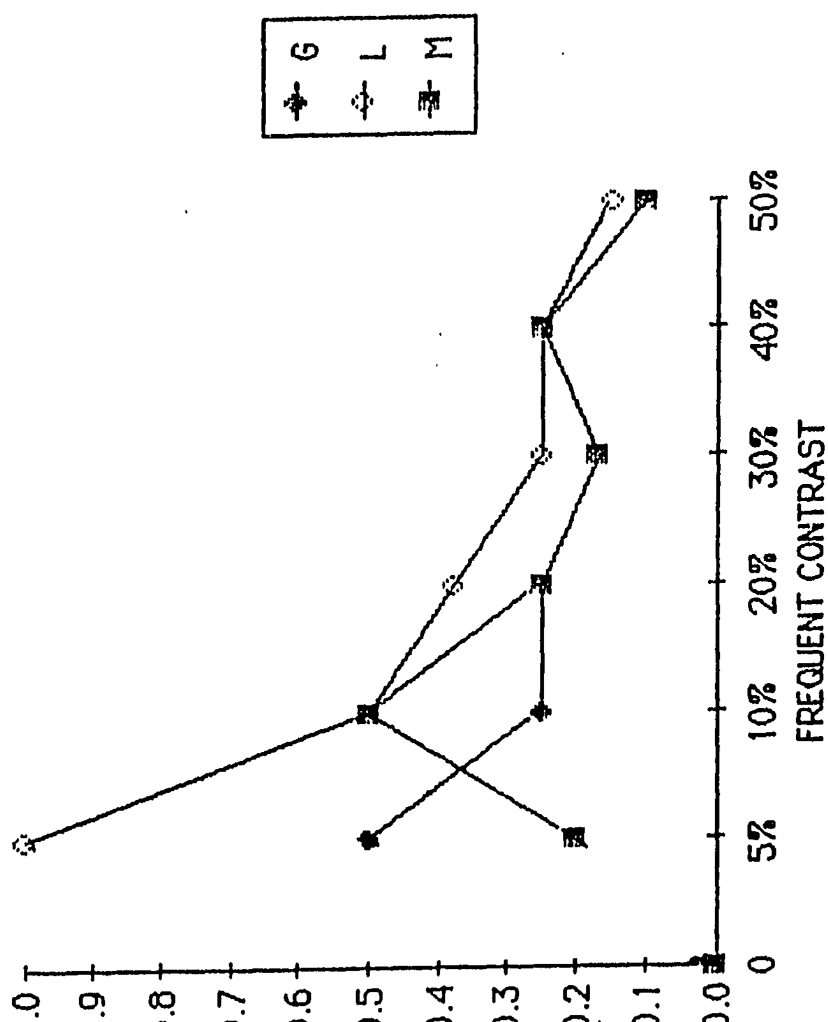
The slopes of the regression lines are:

Observer M: = -.005

Observer G: = -.006

Observer L: = -.015

The mean of these data plotted on log-log coordinates are shown on Figure 33, top.


ERP-JND
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
5%
10%
20%
30%
40%
50%
FREQUENT CONTRAST
G
L
M

than when it was above the frequent contrast (Table 8). The means of the ERP-JNDs below and above the frequent contrast were: for observer M, .245 versus .332, for observer G .295 versus .363, and for observer L .421 versus .495.[8]

In summary then, P3 JNDs are not determined only by ΔC, nor by ΔC/C, although the data suggest that a closer fit could be obtained with the response = f(ΔC).

The Effect of Frequent Contrast

1) The effect of frequent contrast on the latency and amplitude of the ERPs as a function of the ΔC/C for each frequent contrast: The steepest slopes of the regression lines that were fitted to the N2 latency, the P3 latency and the amplitude versus the ΔC/C were for the higher frequent contrasts. Shallower slopes described the functions for the lower frequent contrasts (Figures 18, 19 and 20).

2) The effect of frequent contrast on the latency and amplitude of the ERPs as a function of the ΔC/C across frequent contrasts: If the frequent contrast had an effect, latency should have increased and amplitude should have decreased for a given ΔC as the frequent contrast increased. For instance, for each ΔC, such as ΔC = 5% the ratio of the ΔC to the frequent contrast decreases with an increase in

[8]This difference was not statistically significant; $F(1,5) = 1.114$, $p = .35$, but was noted since this trend was observed in the psychophysical study.

Table 8

The ERP-JND Below and Above the Standard Contrast that Produced Waveforms with Evident P3's

	OBSERVERS					
	M		G		L	
FREQUENT	ERP-JND		ERP-JND		ERP-JND	
CONTRAST	below	above	below	above	below	above
5%	.2	.5	.5	.5	1.*	1.
10%	.5	.5	.5	.5	.5	.75
20%	.25	.375	.25	.375	.375	.375
30%	.167	.167	.167	.25	.25	.33
40%	.25	.25	.25	.25	.25	.313
50%	.1	.2	.1	.3	.15	.2
Ms	.245	.332	.295	.363	.421	.495

*At 5% standard contrast, this observer did not produce a waveform with an evident P3, below the standard.

frequent contrast. A positive function should have been obtained when latency was plotted as a function of the frequent contrast for each ΔC, since as ΔC/C decreases, longer latencies are expected. This occurred for two observers, M and L, the slopes of the functions were +1.425 and +.692, respectively. Whereas when latency was plotted for a particular ΔC/C, such as ΔC/C = .5, as a function of the frequent contrast, a slope of around zero should have been obtained. These results, instead produced negative functions for each of the three observers (The slopes of the functions were -.473, -2.034 and -.58 for M, G, and L, respectively). Appendix C contains these plots.

These data indicate an effect of the frequent contrast on the latency and amplitude measures of the ERPs obtained from the rare presentations both within and across frequent contrasts.

3) The effect of the frequent contrast on the ERP-JND. The frequent contrast also showed an effect on the ERP-JND. The ERP-JND decreased as the standard contrast increased. In addition, if we express the ERP-JND as the just noticeable contrast difference (ΔC) which elicits a P3, it is clear that the ERP growth was not proportional to the frequent contrast. The relationship of the ERP-JND and the psychophysical JND will be discussed later, in Chapter 9.

<u>The Replicability of ERPs</u>

Thus far we demonstrated that latency and amplitude vary with the difference in ΔC. This section answers the question of whether the responses are consistent within observers over a long period of testing in order to demonstrate replicability of the data.

Means and standard deviations of the latency and amplitude were computed for the entire testing period. Regardless of stimulus manipulations, when considering N2 latency, P3 latency and amplitude, the observers remained consistent throughout the nine months of data collection. The shortest latencies for the N2 and P3 at both electrode sites were seen in observer M, while the longest latencies were seen in observer L. The largest amplitudes were produced by subject G.

The N2 latency was shorter at the P_z site (_M_ = 311 msec ±45.7 msec) than at the Z_{63} site (_M_ = 343 msec ±47.7 msec); SEM = 2.95 msec. The Z_{63}-P_z N2 latency difference was +43 msec for M, +21 msec for G and +27 msec for L (Figure 23). The P3 latency did not show a similar difference between the electrode sites; P_z; 454 msec ±39.8 msec and Z_{63}; 459 msec ±45.5 msec; SEM = 2.36 msec (Figure 24). The large standard deviations obtained for the latency measures were due to the nature of this study. Longer latencies were obtained from difficult discriminations, whereas shorter latencies were obtained from easier discriminations.

Figure 23. Each data point represents the latency of the N2 obtained at the P_z site plotted as a function of the latency of the N2 obtained at the Z_{63} site for each of the rare stimulus presentations.

The slope of the regression line represented on this plot = .754. The three observers are represented.

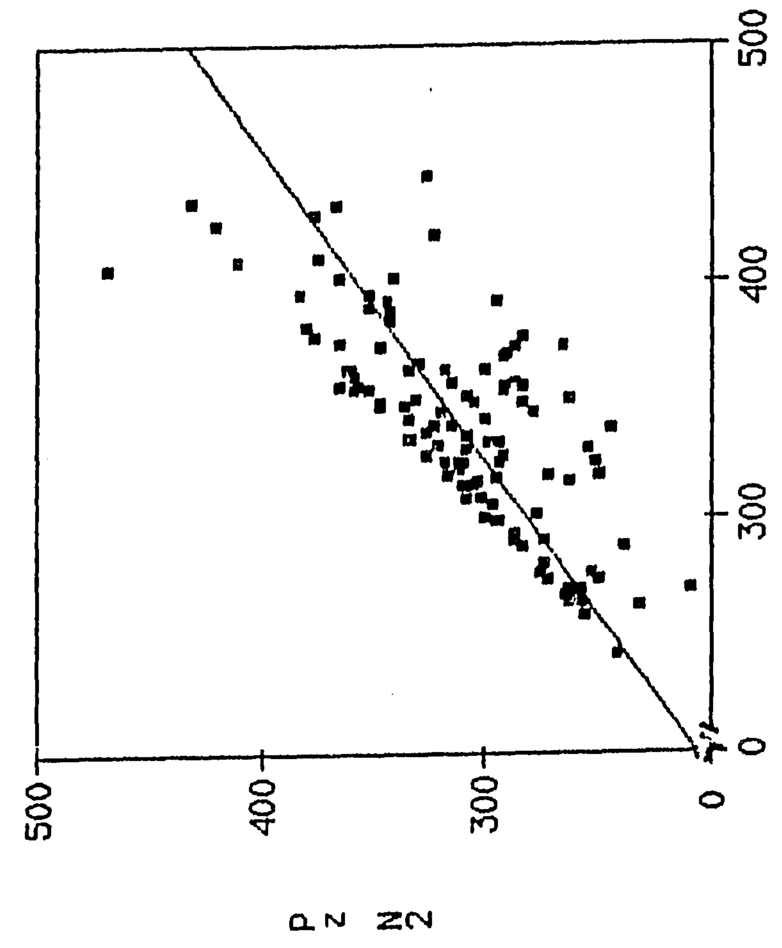
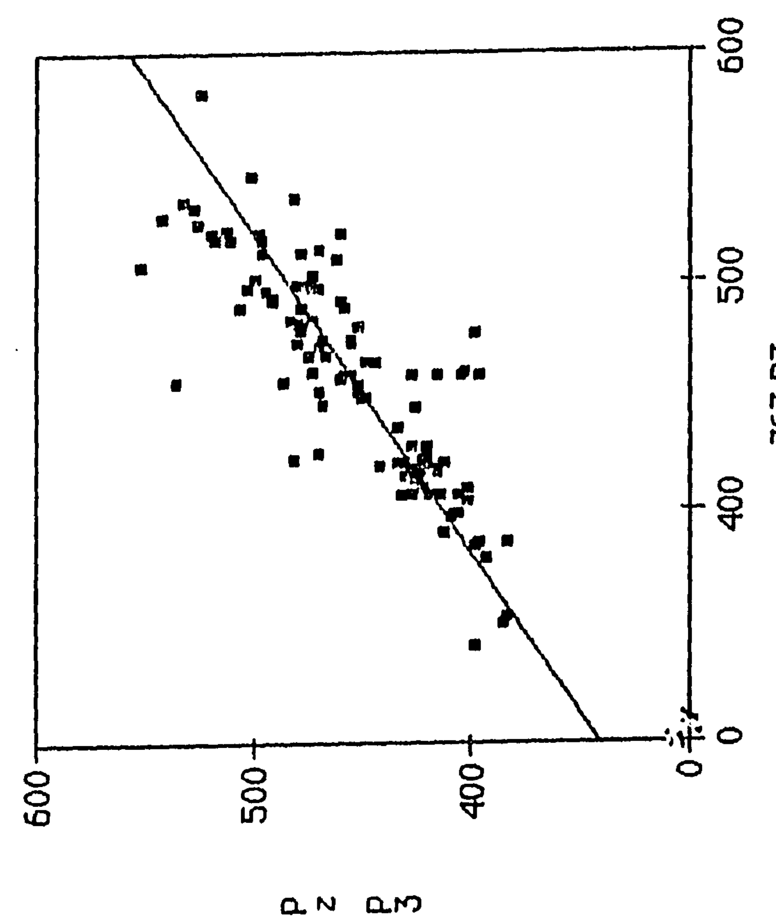

Z63 N2
0
300
400
500
0
300
400
500

Figure 24. Each data point represents the latency of the P3 obtained at the P_z site plotted as a function of the latency of the P3 obtained at the Z_{63} site for each of the rare stimulus presentations.

The slope of the regression line represented on this plot = .72. The three observers are represented.


Z63 P3
0
400
500
600

The peak-to-peak amplitude responses at P_z (9.5 μV ±2.3 μV) were greater than those at Z_{63} (7.6 μV ±3.3μV) for the observers; SEM = .21 μV (Figure 25). The Pearson Product-Moment correlation coefficients obtained between electrode sites were: for N2 latency; r = .751, for P3 latency; r = .84, and for the N2-P3 peak-to-peak amplitude; r = .706 (Table 9).

These data show that P3 latency recorded from P_z or Z_{63} tends to give the same information, whereas N2 latency may provide two types of information, depending on scalp site.

Subtracted Traces

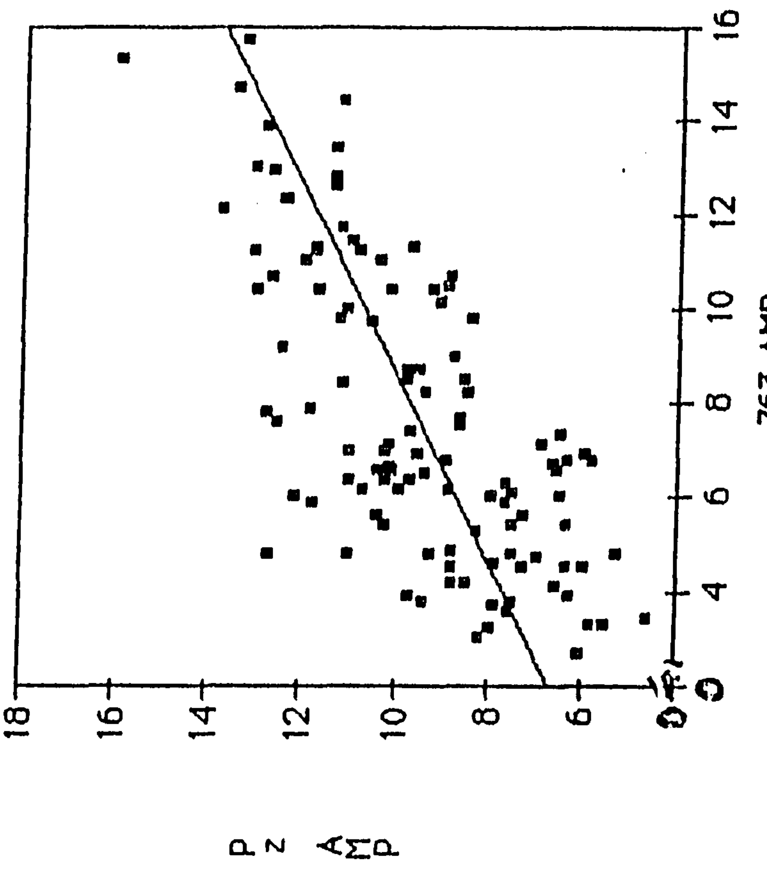
Figures B-2, B-3 and B-8 in Appendix B show subtraction traces superimposed upon the summated traces. Exogenous components are elicited in both the frequent and the rare traces, for instance, those that occur before the N2 are the evoked potentials elicited by the 'onset' and those occurring after the P3 by the 'offset' of the stimulus. Subtractions eliminate components that are common to both frequent and rare traces, except for some residual exogenous components.

The means and standard deviations of the latency and amplitude[9] of the subtracted traces were not different from the rare

[9] The amplitudes derived from the subtracted traces do not represent true amplitude measures, they are the voltage difference between the frequent and the rare traces.

Figure 25. Each data point represents the N2-P3 amplitude obtained at the P_Z site plotted as a function of the N2-P3 amplitude obtained at the Z_{63} site for each of the rare stimulus presentations.

The slope of the regression line represented on this plot = .513. The three observers are represented.



PZ AMP
18
16
14
12
10
8
6
Z63 AMP
4
6
8
10
12
14
16

Table 9

The Correlation Matrix Showing the Relationships between the N2 Latency, the P3 Latency and the N2-P3 Peak-to-Peak Amplitude. The t-Statistic Corresponding to each Correlation is Shown on the Lower Matrix.

	P_z			Z_{63}		
CORRELATION COEFFICIENTS						
P_z						
N2	--	.692	.181	.751	.743	.053
P3		--	.353	.74	.84	.178
AMP			--	.326	.183	.706
Z_{63}						
N2				--	.763	.225
P3					--	.002*
AMP						--
t-STATISTIC t(111) =						
P_z						
N2	--	10.06	-1.94*	11.9	11.7	-.55*
P3		--	-3.96	11.6	16.3	-1.9*
AMP			--	-3.6	-1.9*	10.4
Z_{63}						
N2				--	12.4	-2.426
P3					--	.021*
AMP						--

* Indicates nonsignificant correlation coefficients.

traces. Figures 26, 27 and 28 show the comparisons between the rare and subtracted traces. When a P3 was evident on a rare trace, it was also evident on a subtracted trace, and when a P3 was absent from the rare trace, there was no evidence of a P3 on the subtracted trace. In addition, the subtracted traces showed that the exogenous components had no effect on the N2, P3 or amplitude measures.

Summary of the Results

In summary the results showed that ERPs provide an electrophysiological correlate of suprathreshold visual contrast discrimination. The results showed:

1). P3 waveforms that resemble those seen in the literature were obtained from the observers. P3s were not evident in the traces elicited to the frequent stimulus.

2). For each frequent contrast, the N2 latency, the P3 latency and the peak-to-peak amplitude was plotted as a function of the $\Delta C/C$. As the contrast difference between the rare and frequent patterns increased, the latency of N2 and P3 decreased and the amplitude increased systematically. Since, in each recording session the same contrast level was used as the frequent contrast, and tested with several rare contrasts, it appears that observers maintain a representation of the frequent contrast within each recording session.

3). Frequent contrast showed an effect on the slopes of the

Text continues on page 126.

Figure 26. The means of the N2 latency recorded from the rare and the subtracted traces obtained at the two electrode sites.

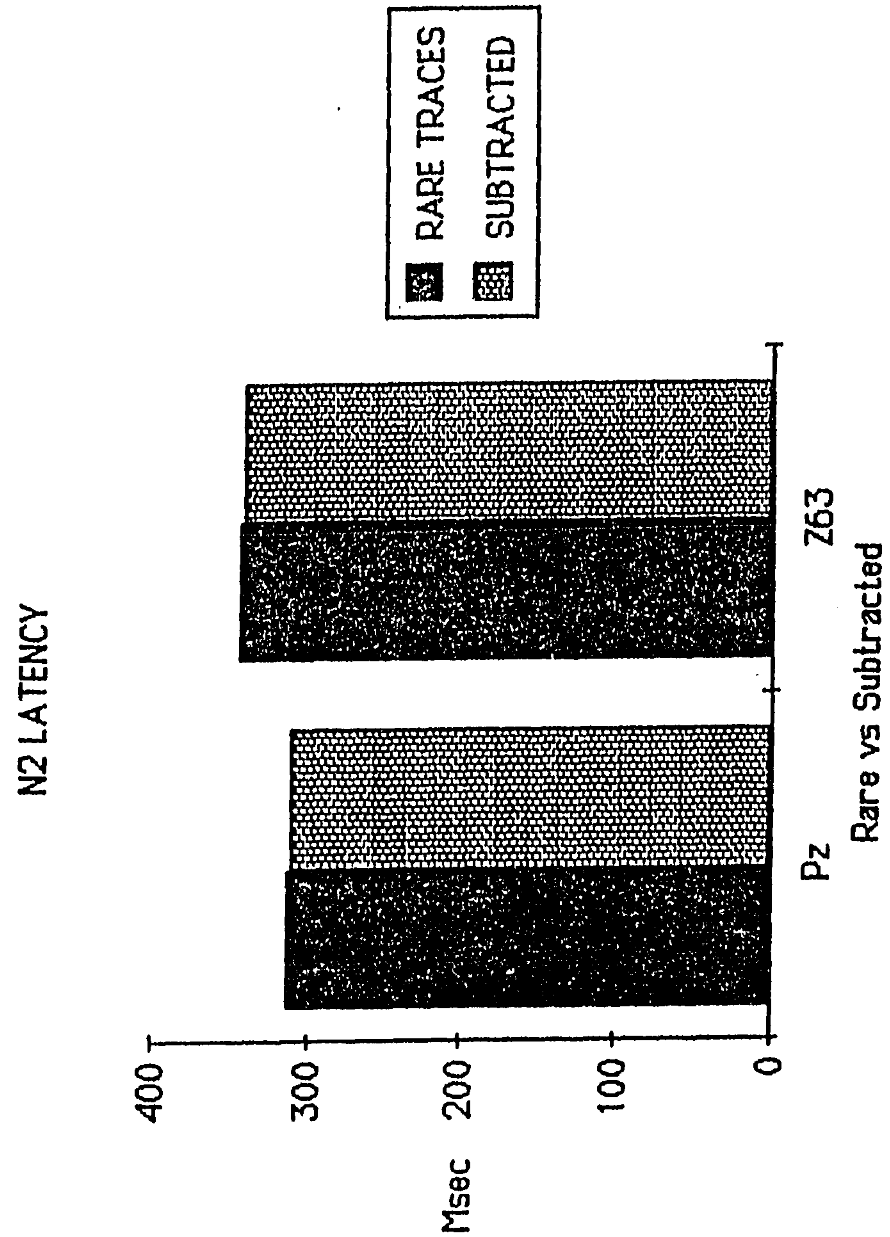

N2 LATENCY
RARE TRACES
SUBTRACTED
Msec
400
300
200
100
0
Pz
Z63
Rare vs Subtracted

Figure 27. The means of the P3 latency recorded from the rare and the subtracted traces obtained at the two electrode sites.

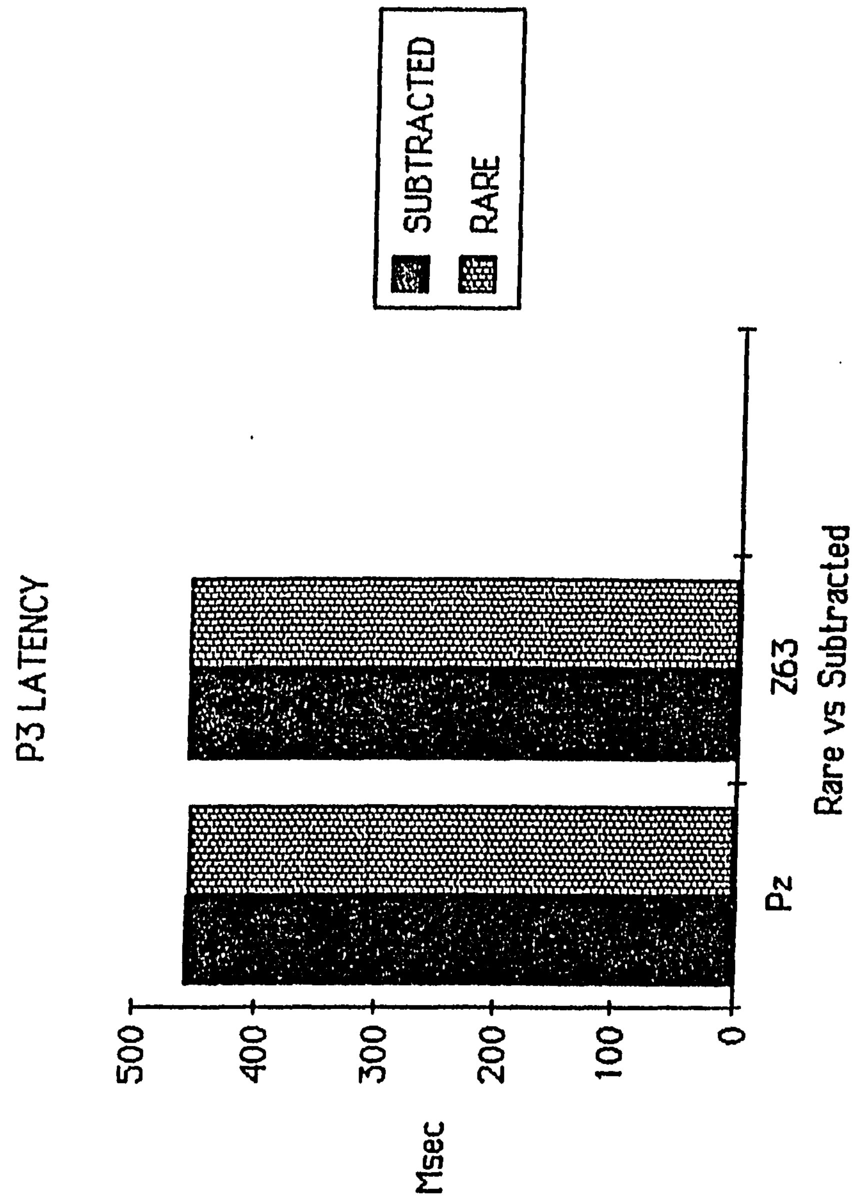
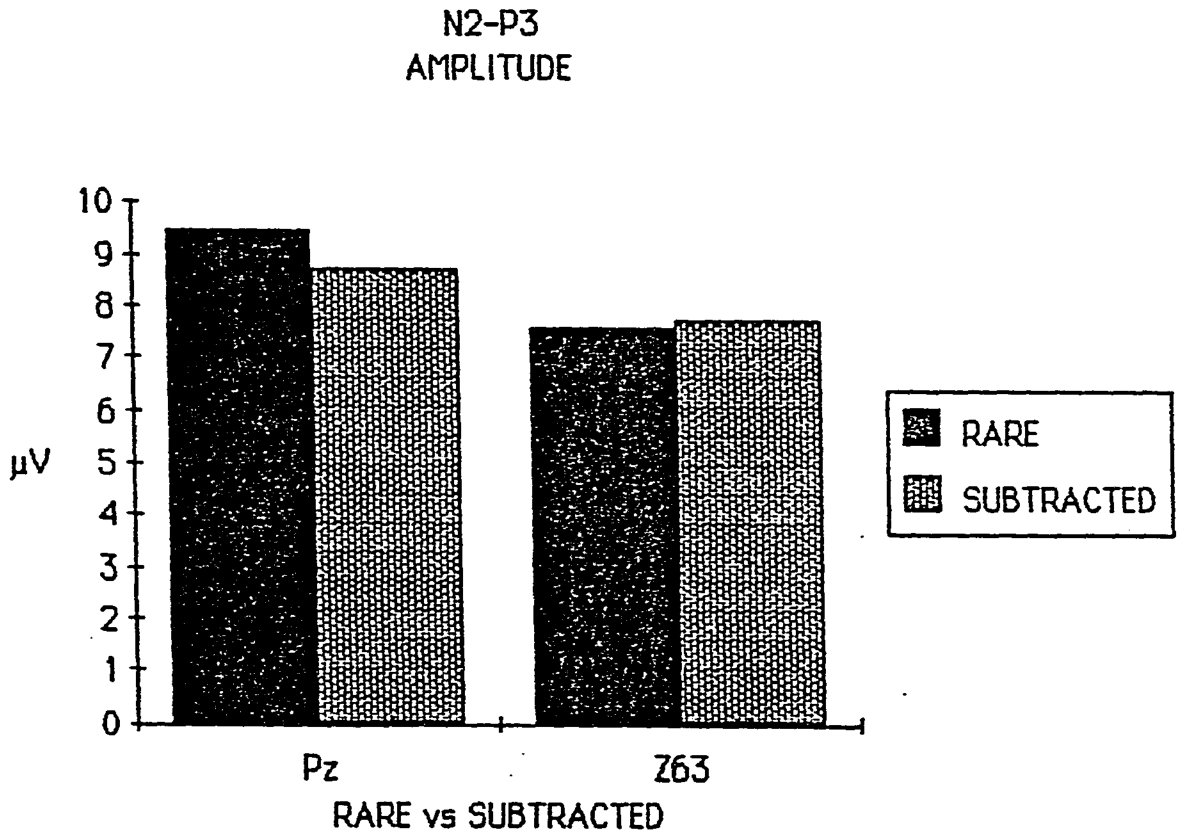

P3 LATENCY
Msec
500
400
300
200
100
0
Pz
Z63
Rare vs Subtracted
SUBTRACTED
RARE

Figure 28. The means of the N2-P3 peak-to-peak amplitude recorded from the rare and the subtracted traces obtained at the two electrode sites.


N2-P3
AMPLITUDE
µV
10
9
8
7
6
5
4
3
2
1
0
RARE
SUBTRACTED
Pz
Z63
RARE vs SUBTRACTED

regression lines plotted for these data. The inclinations of the slopes increased in steepness as the frequent contrast increased from 5% to 50%. This effect was more significant for P3 latency than either N2 latency or peak-to-peak amplitude.

4). The Pearson Product-Moment correlation coefficients showed that P3 latency was more closely related to ΔC/C than N2 latency or N2-P3 peak-to-peak amplitude. Thus P3 latency provided a better index of contrast discrimination than N2 latency.

5). The latency and amplitude of the ERP to the rare stimulus across different frequent contrasts did not remain constant. For any level of ΔC, there was a tendency for the latency to increase and the amplitude to decrease with increasing frequent contrast. For instance, the P3 latency and the peak-to-peak amplitude obtained when the ΔC = 5% and 10% plotted as a function of the frequent contrast increased for two of the three observers.

6). The minimum ΔC/C that the observers required to produce evident P3 waveforms were considered to be the event-related potential - just noticeable difference (ERP-JND). Smaller ERP-JNDs were needed to elicit a P3 as the frequent contrast increased. However, the actual contrast difference (ΔC), between the frequent and the rare stimuli, that was needed to elicit a P3 did not differ for the frequent contrasts of 20%, 30% and 50% (ΔC = 5% for M and G, and ΔC = 7.5% for L), at 40% the three observers required a ΔC of 10%.

7). The N2 latency was significantly earlier at the P_Z electrode site than at the Z_{63} electrode site for all of the observers; the mean difference was 30 msec between the sites. The P3 latency showed no difference between the two recording sites.

8). The subtracted waveforms were not significantly different from the averaged waveforms; nor did they reveal new information.

Chapter 6. The Effect of Varying the *a priori* Probability of Stimulus Occurrence.

Thus far we have demonstrated that N2-P3 amplitude, and to a greater extent, P3 latency relate to suprathreshold contrast discrimination, and to the just noticeable difference of contrast discrimination.

P3 amplitude has been shown to be inversely related to *a priori* probability, in that the lower the probability the higher the amplitude (Courchesne, 1978; Squires, Squires & Hillyard, 1975b; Tueting, Sutton & Zubin, 1971). In order to explore if the same visual stimuli reflect the *a priori* probability of the eliciting event, and also to examine if N2-P3 peak-to-peak amplitude varies in the same manner as the baseline-P3 amplitude, one observer (G) was tested with different probabilities (9:1, 8:2, 7:3 and 6:4). The sinusoidal grating patterns were of the same spatial frequency and mean luminance as the patterns presented in the ERP and psychophysical studies, and they were presented on the same CRT unit. The procedure was identical to that in the electrophysiological study except that the *a priori* probability was varied. To prevent possible confounding of contrast effects, for each probability condition, the contrast of the irrelevant pattern was 50% and the contrast of the target pattern was 10%.

N2-P3 peak-to-peak amplitude varied in the same manner as the baseline-P3 amplitude varies (Tueting, Sutton & Zubin, 1971; Ruchkin & Sutton, 1978): the greatest amplitude occurred with the lowest probability of the target stimulus (11 µV at P_z and 11.4 µV at Z_{63}). As the probability of stimulus occurrence of the target stimulus increased from .1 to .4, the amplitude decreased linearly to 5.9 µV at P_z and 3.2µV at Z_{63}. Amplitude then levelled off with probabilities of .5 and greater. The amplitude at the P_z electrode was greater for each probability condition, with one exception, which was at the lowest probability. Figure 29 shows the amplitude measured at the P_z and the Z_{63} electrode sites plotted as a function of probability of stimulus occurrence.

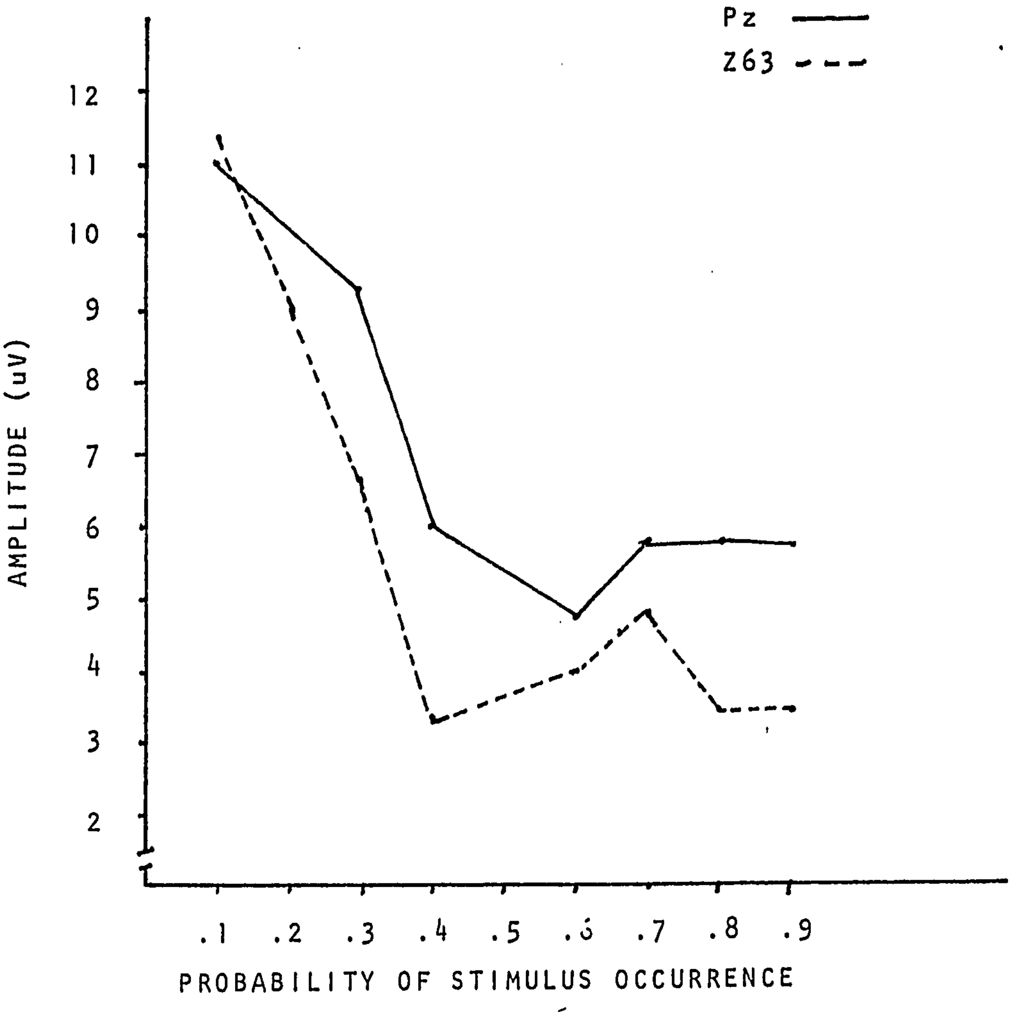
In this study, the P3 latencies did not vary with changes in probability of the target stimulus when it was rare, but decreased when the probabilities were greater than .6.[10] Since P3 latency is considered an index of the speed of information processing (Ritter, Simpson & Vaughan, 1972), this decrease in latency for higher probabilities could have occurred because the target stimulus, being

---

[10]At probabilities greater than .4, the rare stimulus no longer is rare, but, it is still the target stimulus, since in each of these conditions the 10% contrast pattern is always the stimulus that has to be counted.

Figure 29. Peak-to-peak amplitude plotted as a function of the probability of stimulus occurrence.

Note: The solid line represents the amplitude obtained from the P_Z electrode site and the dashed line, the amplitude obtained from the Z_{63} electrode site. The frequent stimulus was always a 50% contrast sinusoidal grating and the rare stimulus was always a 10% contrast sinusoidal grating.


Pz
Z63
AMPLITUDE (uV)
12
11
10
9
8
7
6
5
4
3
2
.1
.2
.3
.4
.5
.6
.7
.8
.9
PROBABILITY OF STIMULUS OCCURRENCE

presented more often, required less information processing. The stimuli were different enough from each other to insure that there would never be uncertainty as to whether or not a target stimulus occurred. The P3 latencies tended to be earlier at the P_Z electrode than at the Z_{63} electrode (Figure 30, top plots).

As opposed to the results of P3, the N2 latency reflected stimulus probability, particularly at the P_Z electrode site (Figure 30, bottom plots). The latency of the N2 showed an inverted "U" function with a peak around .6. The N2 latency was around 300 msec for the lowest and the highest probabilities and increased to 375 msec as the probability of stimulus occurrence became equal. The N2 observed in this study occurred considerably later than N2 latency reported in the literature (Näätänen, Gaillard, & Mäntysalo, 1978, 1980) and considerably later than the Nd wave (Ritter, Ford, Gaillard, Harter, Kutas, Näätänen, Polich, Renault & Rohrbaugh, 1984). The N2 observed in this study appears to be similar to the Nd,[11] since both N2 and Nd are elicited when a stimulus can be distinguished from other stimuli on the basis of simple stimulus characteristics (Näätänen, 1982a).

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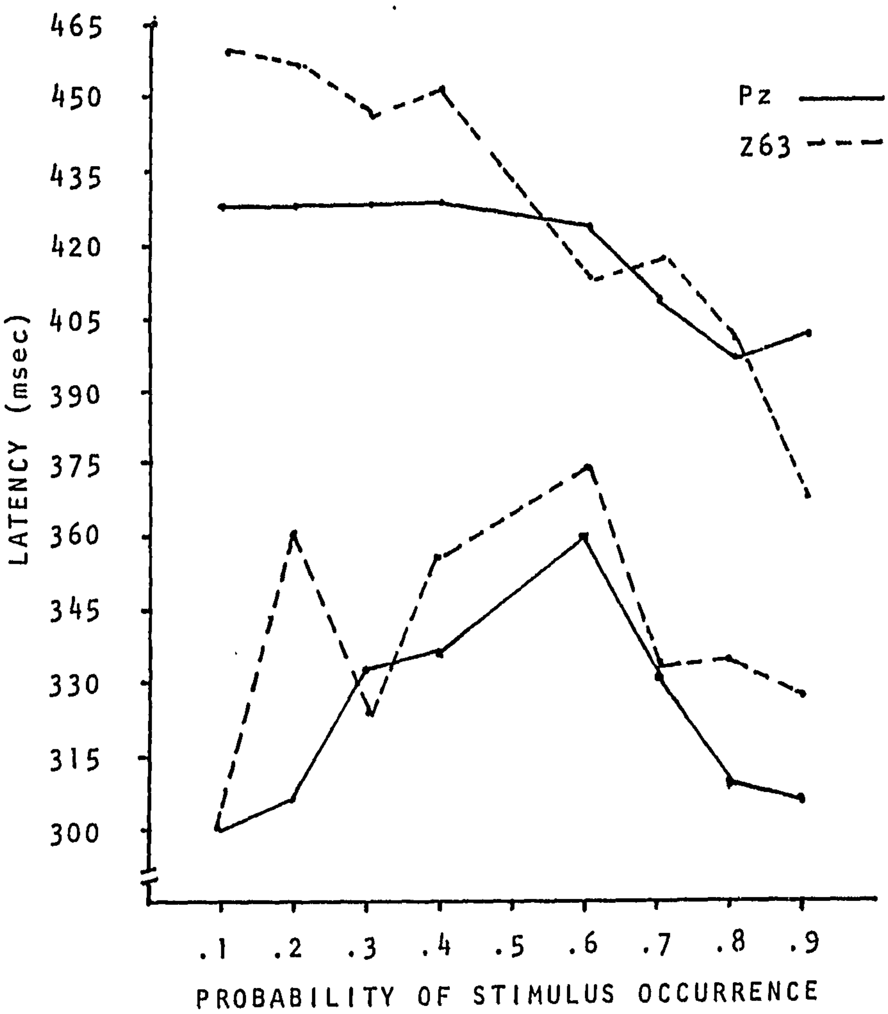
[11] The stimulus modality of most of these studies is auditory. In the visual modality the Nd as well as the visual N1 waves reported in the literature have been recorded from O_Z (Näätänen, 1982b).

Figure 30. Latencies of N2 (bottom) and P3 (top) plotted as a function of the probability of stimulus occurrence.

Note: The solid lines are from the P_Z electrode and the dashed from the Z_{63} electrode.


465
450
435
420
405
390
375
360
345
330
315
300
LATENCY (msec)
Pz
Z63
.1
.2
.3
.4
.5
.6
.7
.8
.9
PROBABILITY OF STIMULUS OCCURRENCE

Hansen and Hillyard (1980) suggested that the onset of the Nd is related to the duration of processing required to determine if a given stimulus is relevant or irrelevant; this might explain the longest latency for the *a priori* probability of .5.

When the stimulus probabilities were not varied, i.e., were always 9:1, while the contrast of the rare patterns was varied, the N2 latency was closely related to the P3 latency (see Table 9, page 97), suggesting that the N2 observed in this study resembles the N2-P3b complex described by Squires, Squires and Hillyard, (1975a). However, for target stimulus probabilities greater than .5, the P3 latency did not change, but the N2 latency decreased with increasing probability. This may have occurred because when a relevant stimulus is presented often, less time is needed to evaluate it, and N2 latency is considered a correlate of stimulus evaluation time (Näätänen & Picton, 1986).

The results of the single observer corresponded with previous P3 studies in that the N2-P3 amplitude resembled baseline-P3 amplitude by showing an inverse relationship with the *a priori* probability of simple visual stimuli presented in an "odd-ball" paradigm.

Chapter 7. Psychophysical Study: Procedure

The method of constant stimuli was employed in this study, and the patterns were presented using the two-alternative forced-choice (2AFC) procedure. This procedure is a psychophysical method which essentially eliminates the need to deal with the observer's criterion (Green & Swets, 1966).

The sinusoidal grating patterns were generated on the same CRT unit used in the electrophysiological study by a Galaxy 2 (Z80 A CP/M Gemini microcomputer) which was designed by Cambridge Research Systems. The gratings were presented using a temporal forced-choice procedure. They were presented in two intervals of 500 msec each, with the second interval immediately following the first. The signal was equally likely to occur in each interval, and the observer was forced to choose an interval. The observers knew that the patterns were presented randomly by the computer, which should have prevented bias towards a particular interval. Only the experimenter knew that in some trials both intervals contained the same contrast. Each interval was announced by an auditory tone.

Each session consisted of 500 two-interval trials with one of two types of tasks: 1) the observer indicated whether the grating appeared to have a higher contrast in the first or the second interval, or 2) the observer indicated which of the two intervals contained the grating of a lower contrast. The rationale for examining lower and higher contrast decisions was to see if these judgements would affect the JND. This also provided an opportunity to compare these judgements with the lower and higher contrast differences that produced P3s of the smallest magnitude and to examine if the observers replicated their performance.

In a pilot study, the values of the comparison stimuli were determined so that with each standard, the stimulus value of the highest contrast would be judged greater than the standard in over 95% of the trials, and the stimulus value of the lowest contrast would be judged smaller in over 95% of the trials. The pilot study resulted in comparison stimuli values that are shown on Table 10. Nine contrasts of the comparison stimuli were presented with each standard. Step size was determined by the formula: (max-min)/8, which gave equal contrast intervals between the comparison stimuli. Max is the greatest magnitude and min is the least magnitude.

The observers held a box with three response keys; a red key (on the left) represented the first interval, a blue key (on the right) represented the second interval and a white key (in the center) which the observers pressed if the trial was not attended. The unattended trial was not considered by the computer, and it was then replaced with an additional trial. The observers indicated their choice of interval by pressing one of the two response keys (either the red or

Table 10

The Standard Contrasts and the Lowest and Highest Comparison Contrasts that were Presented to the Observers in the Psychophysical Study.

STANDARD CONTRAST	COMPARISON CONTRASTS LOWEST	COMPARISON CONTRASTS HIGHEST
5%	2.5%	7.5%
10%	7%	13%
20%	15%	25%
30%	22.5%	37.5%
40%	30%	50%
50%	40%	60%

the blue key) after a different tone was presented; this different tone indicated that the response should be made.

Stimulus presentation was computer controlled such that the standard stimulus was randomly assigned to either the first or the second interval, and the comparison stimulus was assigned to the other interval. The data were collected and analyzed by the computer. An example of a computer printout which consisted of: each trial, the contrast presented, in which interval it was presented, and the subject's response, is shown in Table 11.

Each session, which consisted of the presentation of one standard contrast with one type of response required of the observer in 500 trials, took at least 50 minutes. These sessions were presented randomly, interspersed with the electrophysiological sessions. Data collecting took about nine months. Each observer generated 12 functions, two for each standard contrast, one requiring responses to the higher contrast and the other requiring responses to the lower contrast.

Data Analysis

The psychophysical data obtained from computer printouts were used to generate psychometric functions. The percentage of trials a comparison contrast was considered higher, or lower (depending on the task) than the standard contrast was plotted as a function of the comparison contrasts. The contrast values corresponding to 25%, 50%

Table 11

An Example of the Output Generated by the Galaxy Microcomputer

SPATIAL FREQUENCY = 2.3 C/D
STANDARD CONTRAST = 5

TRIAL	CONTRAST	INTERVAL	RESPONSE
1	3.125	1	correct
2	6.25	1	correct
3	5	2	equal
4	6.25	2	correct
5	6.875	1	correct
6	2.5	1	correct
7	6.875	2	correct
8	6.875	2	correct
9	3.75	1	correct
10	4.375	1	ERROR
11	3.75	2	correct
.	.	. .	....
.	.	. .	....
.	.	. .	....
.	.	. .	....
50	5.625	1	ERROR

Table 11. In this example, the stimulus had a spatial frequency of 2.3 c/d, and the standard contrast was 5%. The numbers under the heading INTERVAL tell in which interval the comparison stimulus was presented. The response "equal" refers to a trial in which the comparison stimulus was the same as the standard.

and 75% correct were obtained from each psychometric curve. The difference between the standard contrast and the values obtained at 25% and 75% on each curve were considered the difference thresholds. These difference thresholds were divided by the standard contrast to give Weber's ratios (JND). For each psychometric function, two Weber's ratios were obtained, the lower JND at the ratio corresponding to 25% and the upper JND at 75%, when the task was to respond to the higher contrast. When the response was to the lower contrast, the lower JND was obtained at 75% and the upper at 25%. Each observer produced four JNDs from each standard contrast, two from "greater than" and two from "less than" responses.

Pearson correlation coefficients were calculated to determine whether or not a relationship exists between: 1) the JNDs derived from the "greater than" responses versus the standard contrasts, and the JNDs derived from the "less than" responses versus the standard contrasts; 2) the JNDs derived from the responses to the higher contrast versus the JNDs derived from responses to the lower contrast, to see if the data replicate; 3) the upper limens versus the standard contrast and the lower limens versus the standard contrast because upper and lower sensitivity may be different, since this tendency was seen in the electrophysiological study;[12] 4) the upper limens versus the lower limens; 5) the number of errors produced within the first 125 trials versus the number of errors produced within the last 125 trials.

Repeated-measures ANOVAs were performed on the JNDs to determine whether or not there would be an effect of observers, type of response, or standard contrast.

The slope of each psychometric function within the area of uncertainty (between the upper limen and the lower limen) was obtained and subjected to an ANOVA which investigated the effect of observer and standard contrast.

The number of errors was calculated for each standard contrast and subjected to an ANOVA to determine the effect of observer and standard contrast. The errors produced within the first 125 trials and within the last 125 trials of each session were calculated and repeated-measures ANOVAs were conducted on the errors to determine if observer differences, or the beginning or the end of the session, with the repeated measure, standard contrast were statistically significant.

Signal detection analysis was not employed because: 1) the observers produced few errors,[13] 2) the criterion was not varied and

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[12]Pearson correlation coefficients were used as an index of dependence rather than its more conventional statistical application since the standard contrast is not dependent.

3) only one single pair of hit and false alarm probabilities could be determined for each ROC curve. It is known that the area of the ROC curve which has been estimated by a single pair of hit and false alarm probabilities is not as sensitive as the proportion of correct responses in a 2AFC task (McNicol, 1972, pp. 45-46; Green & Swets, 1966).

[13] In most of the sessions the proportion of errors was less than 10%.

Chapter 8. Results of the Psychophysical Study

The psychometric functions of each observer had steeper slopes as the standard contrast decreased. The psychometric functions averaged over the three observers for "greater than" responses are shown on Figure 31 and for "less than" responses on Figure 32. The dashed lines on these figures represent the 25% and the 75% limens on the ordinate. The contrast values of the upper and lower limens were obtained from vertical lines drawn from 25% and 75% on the psychometric functions to the abscissa. The contrasts indicated from these vertical lines were subtracted from the standard used for each function, and the absolute value that was derived was then divided by the standard contrast in order to get Weber's ratios ($\Delta C/Cs$), the JND at each standard contrast. Appendix D displays these functions.

The JND

The expected result (Stevens, 1951), that the JNDs are larger at low contrast levels, were obtained. Regardless of the type of response required (i.e., "greater than", see Table 12; or "less than", Table 13), and as the standard contrast increased, the variability in responding decreased; M = .0955, ±.0277 for "greater" responses and M = .104, ±.024 for "lesser" responses at 5% standard contrast; while at 50% standard contrast, the means were .0355 ±.007 for "greater"

Text continues on page 151.

Figure 31. The psychometric functions obtained by the three observers when the task was to indicate in which of the two intervals a higher contrast was presented.

Each function consists of 1500 two-interval trials, 500 trials from each observer.

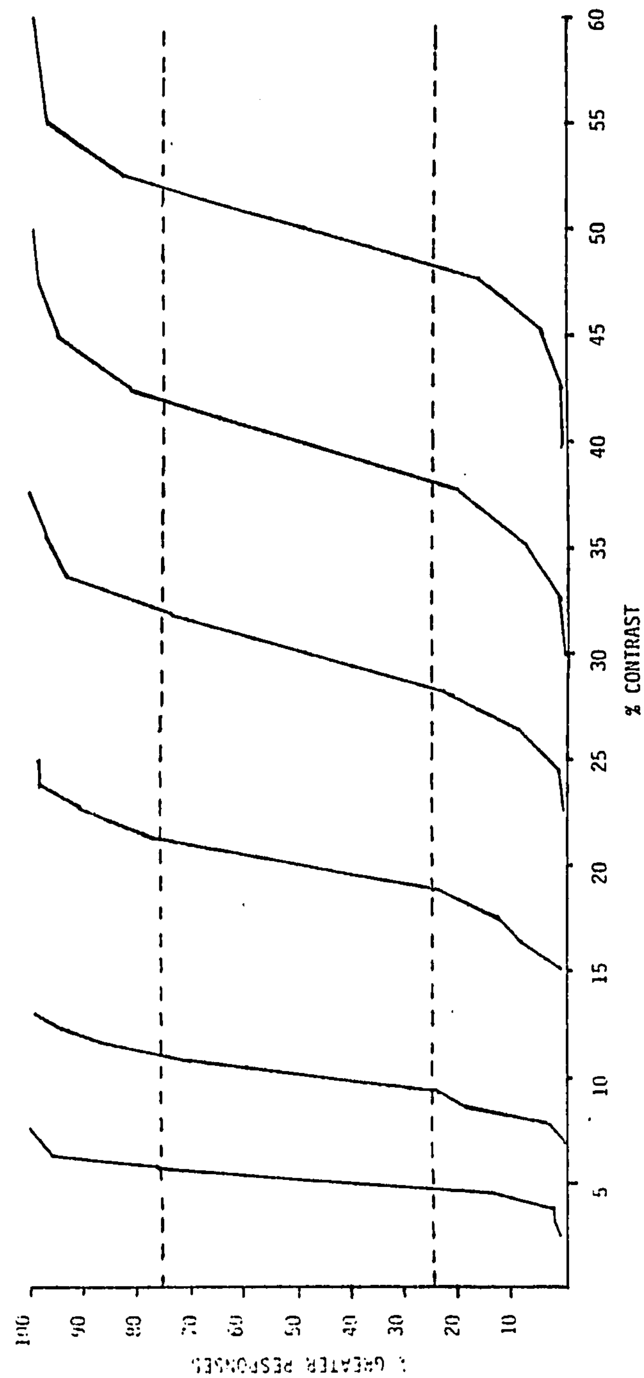

% CONTRAST
5
10
15
20
25
30
35
40
45
50
55
60
10
20
30
40
50
60
70
80
90
100

Figure 32. The psychometric functions obtained by the three observers when the task was to indicate in which of the two intervals a lower contrast was presented.

Each function consists of 1500 two-interval trials, 500 trials from each observer.

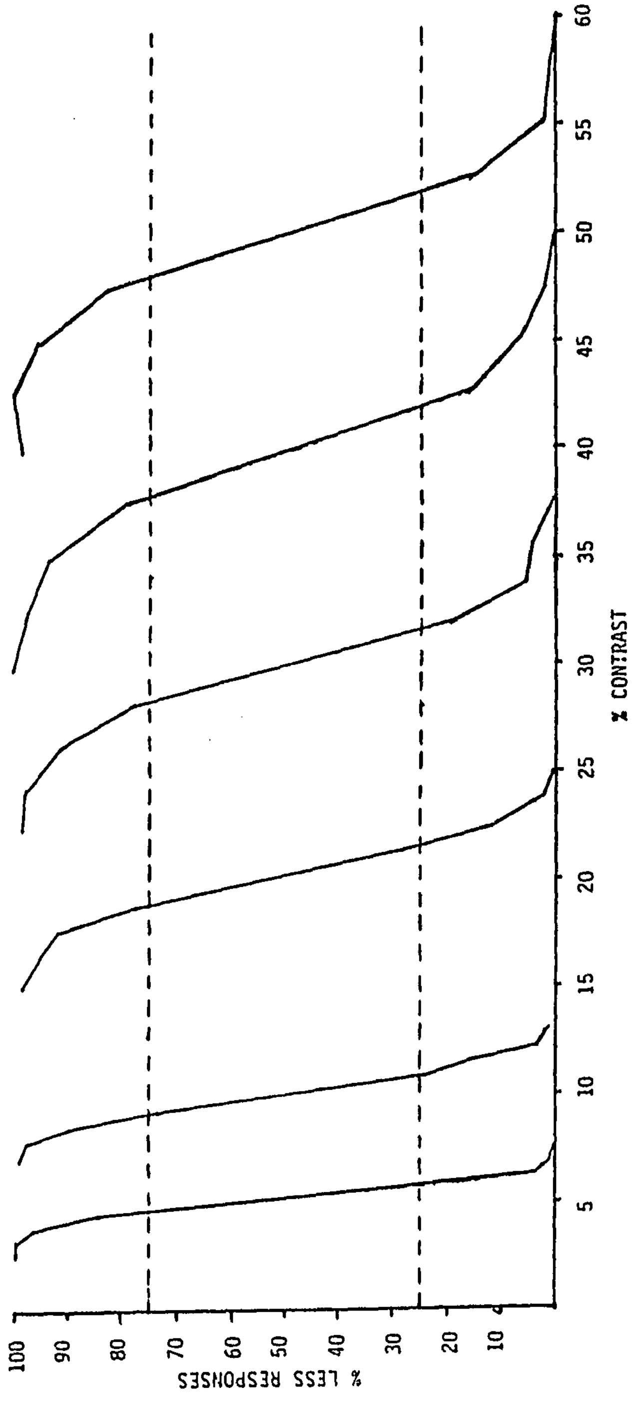

% CONTRAST
5
10
15
20
25
30
35
40
45
50
55
60
% LESS RESPONSES
100
90
80
70
60
50
40
30
20
10

Table 12

The JNDs Obtained by Each Observer When the Task was to Respond to the Greater Contrast

STANDARD CONTRAST	M DL_L	M DL_U	G DL_L	G DL_U	L DL_L	L DL_U
5%	.0875	.1	.05	.125	.0875	.123
10%	.086	.1125	.06	.0675	.0675	.113
20%	.034	.059	.05	.05	.1	.084
30%	.044	.072	.057	.063	.069	.069
40%	.044	.0375	.08	.05	.0375	.056
50%	.0275	.03	.04	.045	.035	.043

DL_L = the lower difference limen

DL_U = the upper difference limen

Table 13

The JNDs Obtained by Each Observer When the Task was to Respond to the Lower Contrast

STANDARD CONTRAST	OBSERVERS M DL_L	M DL_U	G DL_L	G DL_U	L DL_L	L DL_U
5%	.08125	.1	.075	.125	.106	.138
10%	.06	.0375	.135	.1275	.06	.12
20%	.075	.075	.1	.1	.0469	.1
30%	.047	.04	.056	.053	.106	.063
40%	.0375	.034	.075	.075	.04375	.059
50%	.04	.03	.035	.0475	.045	.038

responses and .03925 ±.006 for "lesser" responses. The overall means, including both types of response, were; $\underline{M}$ = .102 ±.03 and $\underline{M}$ = .039 ±.005 for 5% and 50% respectively (Table 14). There was no statistical effect of type of response on the JND; $\underline{F}(1,3) = 4.074$, $\underline{p}$ = .1369. Yet, if the observers had responded similarly between the two types of task ("greater than" vs "less than"), then a higher probability level should have been obtained. Figure 33 shows the JND versus the standard contrast for responses to the higher contrast and Figure 34 shows these relationships for responses to the lower contrast. The JNDs obtained from the "greater" responses correlated statistically with the "lesser" responses; $\underline{r}$ = .549, $\underline{t}(35) = 3.8$, Figure 35 displays this relationship.

The repeated-measures ANOVA which investigated the effect of type of response ("greater than" versus "less than"), observers, and standard contrast on the JNDs showed no effect of observer, or type of response; but did show a strong effect for standard contrast (Table 15). The observers were given both tasks in order to see if they would replicate their performance. They did not perform statistically different between tasks.

The Slopes of the Psychometric Functions

The slopes of the psychometric functions within the area of uncertainty (between 25% and 75% correct) decreased in steepness as

Text continues on page 160.

Table 14

Means and Standard Deviations of the JNDs of the Three Observers at Each Standard Contrast

Standard Contrast	Lower Limen		Upper Limen		Difference Limen	
	M	SD	M	SD	M	SD
5%	.08125	.0185	.1229	.0267	.102	.03
10%	.078	.0296	.1056	.024	.0918	.029
20%	.0677	.028	.071	.0276	.0694	.027
30%	.058	.02	.0672	.02	.0616	.017
40%	.058	.02	.0484	.008	.053	.016
50%	.0383	.004	.04	.005	.0394	.005

Table 14. Ms and SDs for the three observers of the lower and upper limens under both conditions, "greater" and "lesser" responses. The difference limen is the average of all of the responses at each standard contrast.

Figure 33. The JNDs(10^3) obtained when the observers task was to respond to the higher contrast plotted as a function of the standard contrasts.

The slope of the function is -.001, and the intercept of .096.
Note: The three observers produced a total of six data points for each standard contrast; these six may not be clearly discerned because more than one data point may be at the same location.

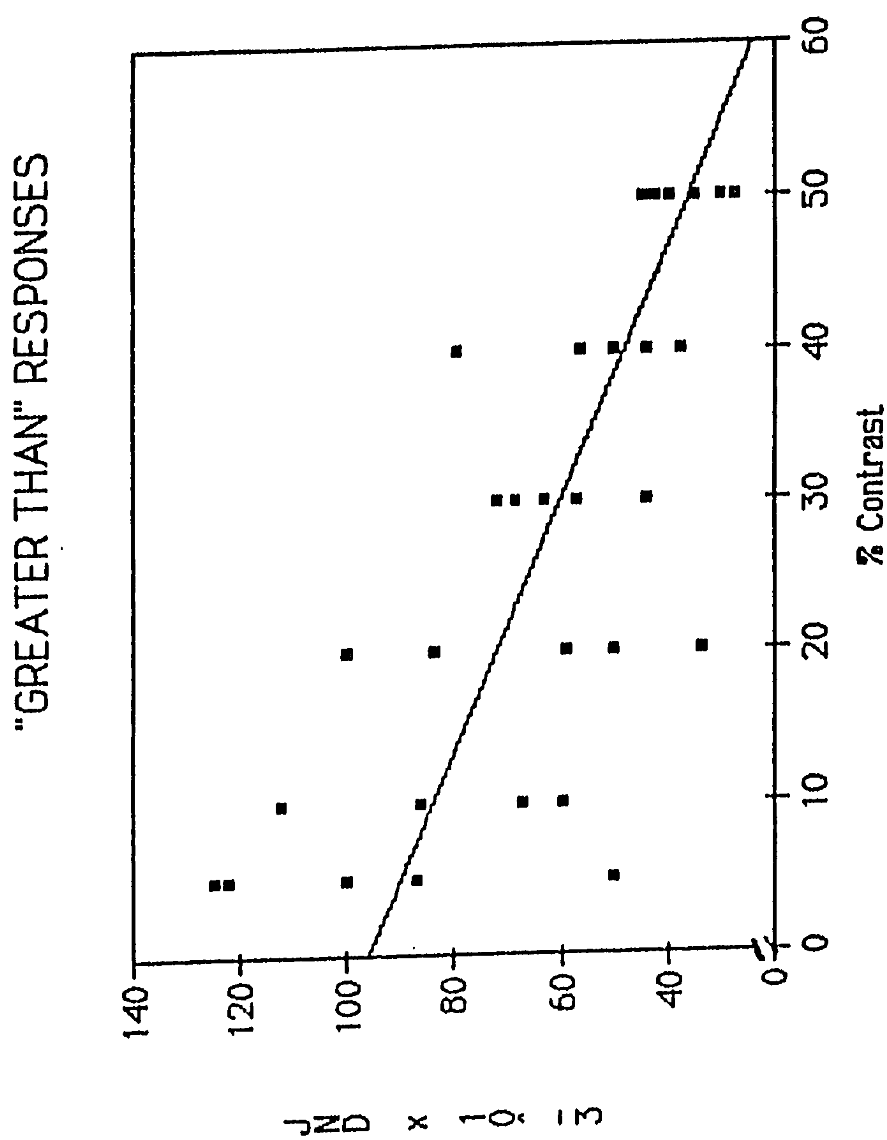

"GREATER THAN" RESPONSES
140
120
100
80
60
40
0
0
10
20
30
40
50
60
% Contrast

Figure 34. The JNDs(10^3) obtained when the observer's task was to respond to the lower contrast plotted as a function of the standard contrasts.

The slope of the function is -.001, the intercept is .108.
Note: The three observers produced a total of six data points for each standard contrast; these six may not be clearly discerned because more than one data point may be at the same location.

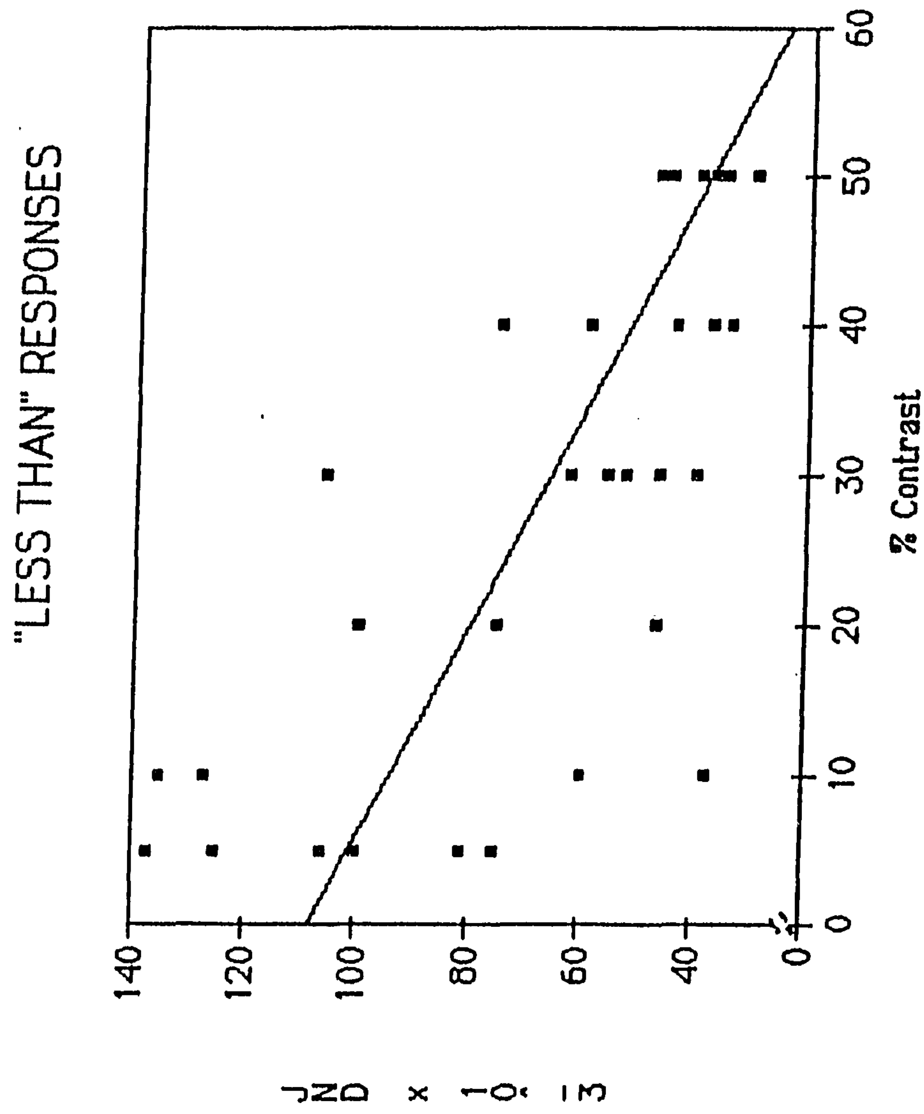

"LESS THAN" RESPONSES
JND x 10-3
0
20
40
60
80
100
120
140
0
10
20
30
40
50
60
% Contrast

Figure 35. The JNDs(10^3) obtained from "less than" responses plotted as a function of the JNDs(10^3) obtained from "greater than" responses.

The Pearson product-moment correlation of these data are: $r = .549$, $t(35) = 3.8$.

Note: Each data point represents either the upper or the lower DL obtained from "less than" responses plotted against the same DL obtained from "greater than" responses.

"LESS THAN" RESPONSES x "GREATER THAN" RESPONSES

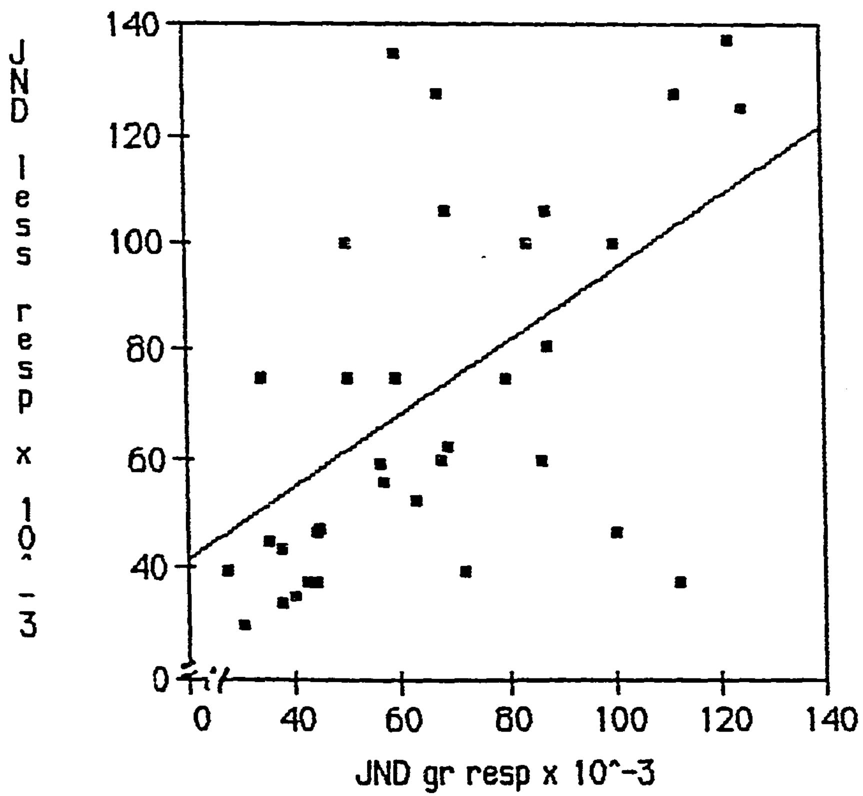


Table 15

Summary Table of the Repeated Measures ANOVAs Which Examined the Effect of Response ("Greater Than" vs "Less Than"), and the Standard Contrast, Between Observers on the JNDs

Source	SS	df	MS	F	p
(A) Observer	.004	2	.002	2.604	.2209
Error	.002	3	.001		
(B) Response	.001	1	.001	4.074	.1369
A x B	.003	2	.001	6.972	.0745
Error	.001	3	.000	Epsilon Correction 1.00	
(C) Contrast	.031	5	.006	12.668	.0001
A x C	.003	10	.000	.584	.8029
Error	.007	15	.000	Epsilon Correction .20	
B x C	.001	5	.000	.891	.5113
A x B x C	.008	10	.001	4.148	.0068
Error	.003	15	.000	Epsilon Correction .20	

the standard contrast increased, as was expected. The means of the slopes decreased from an incline of 48.9 ±7.5 for each percentage of contrast when the standard contrast was 5% to an incline of 13.9 ±1.9 for each percentage of contrast when the standard contrast was 50% (Table 16). Standard contrast showed a significant effect; $\underline{F}(5,15)$ = 33.314, $\underline{p}<.000$, on the slopes of the psychometric functions (Table 17). Figure 36 shows the means of the slopes of the psychometric functions obtained at the six standard contrasts. The degree of inclination of the slopes approach asymptote when the standard contrast is 20%, i.e., above 20% contrast the inclination of the slopes of the psychometric functions tend to be similar. This indicated that even though the $\Delta C/C$ tends to decrease as the standard contrast increases, the ΔC tends to remain the same between standard contrasts of 20% and 50%.

The Errors

The number of errors produced by each observer was reflected in the slopes within the area of uncertainty of the psychometric functions; for each standard contrast, the functions with the steeper slopes corresponded with less errors (Figure 37).

The number of errors varied over observers: L produced the most, $\underline{M}$ = 43 ±19.5; G's errors were, $\underline{M}$ = 39.5 ±18; and M produced the least errors, $\underline{M}$ = 19.4 ±13.7. The observer effect on the

Text continues on page 167.

Table 16

The Slopes of the Psychometric Functions Within the Areas of Uncertainty Compared to the Standard Contrasts for "Greater Than" Responses and "Less Than" Responses

	OBSERVERS					
	M		G		L	
Standard	slopes		slopes		slopes	
Contrast	>	<	>	<	>	<
5%	53.6	56	56	48	40	40
10%	27	50	39	15	26.7	32
20%	26	18	26	9	13	17
30%	15	19	13.6	13	12.5	14.4
40%	15.8	17.6	9	11	12.6	9.4
50%	16.8	15.4	14.4	12.4	12.2	12.2

> "Greater than" responses.

< "Less than" responses.

Table 17

The Repeated-Measures ANOVAs Which Examined the Effect of Observers and Standard Contrast on the Slopes of the Psychometric Functions Within the Areas of Uncertainty.

Source	SS	df	MS	F	p
(A) Observers	345.696	2	172.848	2.075	.2718
Error	249.950	3	83.317		
(B) Contrast	6192.782	5	1238.556	33.314	.0000
A x B	185.311	10	18.531	.498	.8657
Error	557.680	15	37.179		

Epsilon Correction .2

Figure 36. A comparison of the means of the slopes of the psychometric functions obtained at the six standard contrasts for the three observers.

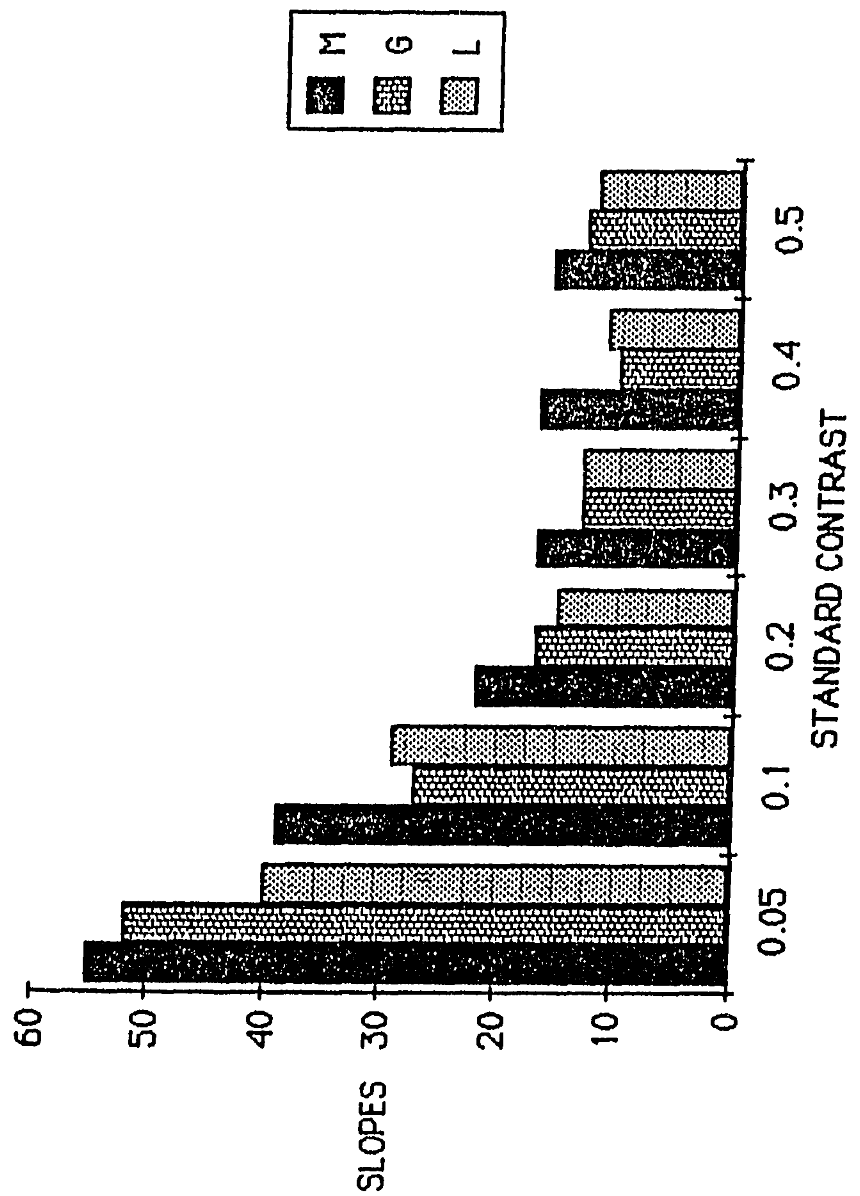
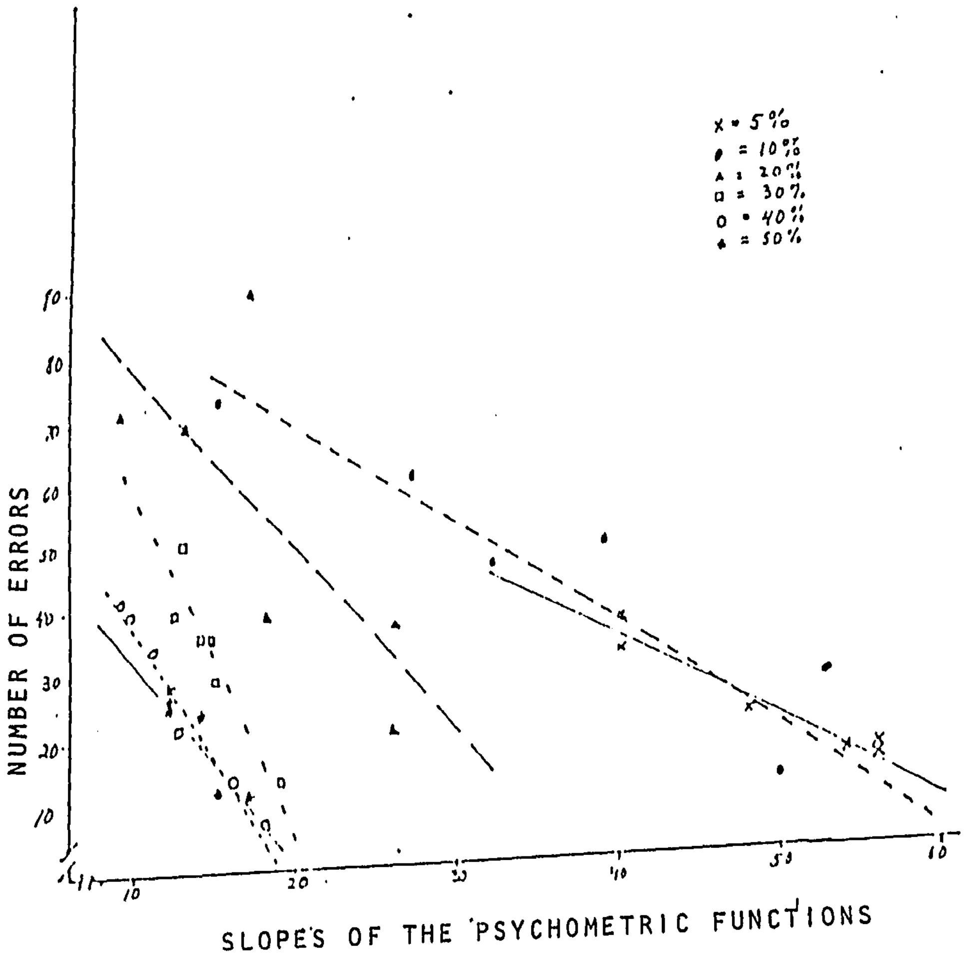

M
G
L
60
50
40
30
20
10
0
SLOPES
0.05
0.1
0.2
0.3
0.4
0.5
STANDARD CONTRAST

Figure 37. The number of errors plotted as a function of the slopes of the psychometric functions. Each function represents one standard contrast.

The slopes, intercepts and correlation coefficients for these data are:

Standard Contrast	Slope	Intercept	Correlation Coefficient
5%	-1.3	84.7	-.98
10%	-1.65	100	-.946
20%	-2.9	105.8	-.764
30%	-5	105	-.92
40%	-3.8	75	-.99
50%	-3.25	62	-.919


x = 5%
= 10%
= 20%
= 30%
= 40%
= 50%
NUMBER OF ERRORS
90
80
70
60
50
40
30
20
10
10
20
30
40
50
60
SLOPES OF THE PSYCHOMETRIC FUNCTIONS

number of errors just missed statistical significance; $F(2,3) = 8.855$, $p = .0551$. There was a main effect of the standard contrast on the number of errors; $F(5,15) = 8.589$, $p = .0005$ (Table 18 and Figure 38). The relationship between errors and standard contrast showed a negative linear function between 10% and 50% standard contrast. The errors decreased as the standard contrast increased. These results differed from Kulikowski (1976), who found that errors increased when the standard pattern had a higher contrast.

Each observer produced more errors within the first 125 trials than the last 125 trials. The number of errors produced within the first 125 trials correlated positively with the number produced within the last 125 trials; $r = .691$. The repeated-measures ANOVAs which investigated the errors produced in the first 125 trials versus the errors produced in the last 125 trials, by the three observers with the repeated-measure, standard contrast, indicated no effect for the difference between observers ($F(2,3) = 6.073$, $p = .0882$); while the beginning versus the end of the session also just missed significance ($F(1,3) = 8.565$, $p = .0612$) (Table 19). Standard contrast showed a statistically significant effect on the errors in the beginning versus the end; $F(5,15) = 5.166$, $p = .0059$. These analyses produced an unexpected result, in that the standard contrast showed a main effect on the number of errors that the observers made. This effect was

Text continues on page 172.

Table 18

The Repeated-Measures ANOVA Which Examined the Errors of the Observers by the Six Standard Contrasts

Source	SS	df	MS	F	p
(A) Observers	3887.056	2	1943.528	8.855	.0551
Error	658.417	3	219.472		
(B) Contrast	5829.139	5	1165.828	8.589	.0005
A x B	1446.278	10	144.628	1.065	.4417
Error	2036.083	15	135.739		

Epsilon Correction .20

Figure 38. The means of the errors plotted as a function of the standard contrast.

Each data point represents the mean of the errors from six sessions; three observers and two types of response ("greater than" or "less than").

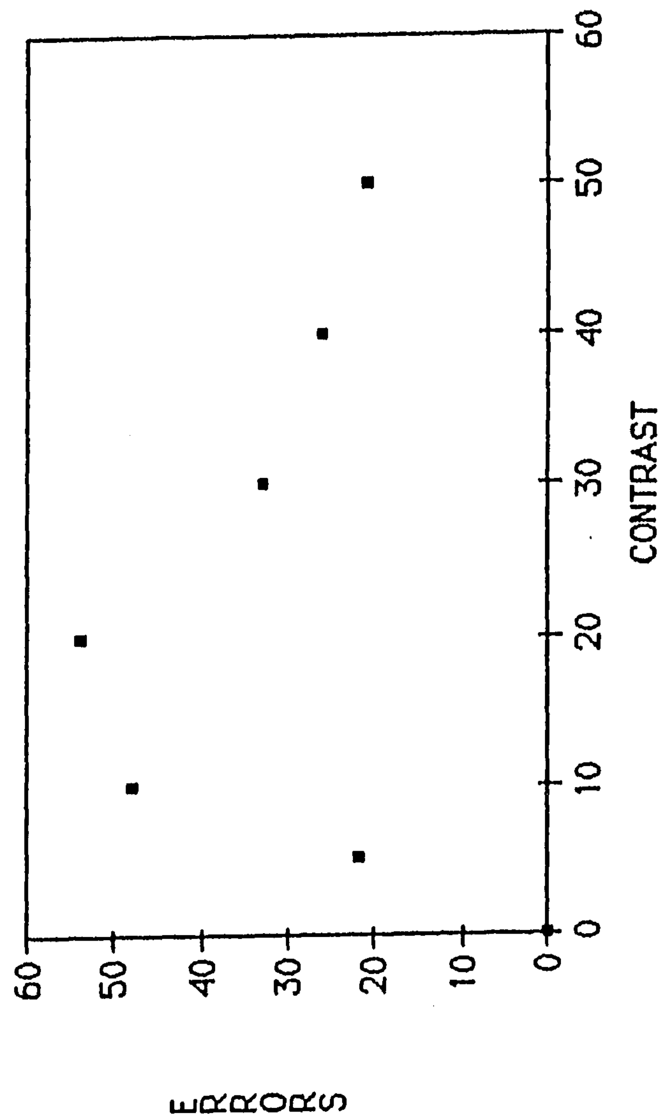

60
50
40
30
20
10
0
ERRORS
0
10
20
30
40
50
60
CONTRAST

Table 19

The Repeated-Measures ANOVA Which Examined the Errors Obtained in the First 125 Trials Versus the Errors Obtained in the Last 125 Trials by Observer and the Six Standard Contrasts

Source	SS	df	MS	F	p
(A) Observer	556	2	278	6.073	.0882
Error	137.333	3	45.778		
(B) Beg vs End	128	1	128	8.565	.0612
A x B	36.333	2	18.167	1.216	.4105
Error	44.833	3	14.944	Epsilon Correction 1.	
(C) Contrast	566.833	5	113.367	5.166	.0059
A x C	43.167	10	4.317	.197	.9934
Error	329.167	15	21.944	Epsilon Correction .2	
B x C	74.333	5	14.867	2.871	.0516
A x B x C	73.833	10	7.383	1.426	.2589
Error	77.667	15	5.178	Epsilon Correction .2	

demonstrated by the decreasing number of errors as the standard contrast increased from 10% to 50%.

Summary of the Psychophysical Results

In summary, the psychophysical results showed:

1) The observers produced psychometric functions of the expected ogive shape.

2) The JNDs and the variability decreased with increases in the standard contrast.

3) The slopes of the psychometric functions within the area of uncertainty decreased as the standard contrast increased to 20%; then, between 30% and 50% contrast, the inclinations of the slopes remained similar (i.e., even though the JNDs decreased, the ΔCs tended to remain the same for these standard contrasts).

4) The number of errors correlated negatively with steepness of slopes; for each standard contrast the steeper slopes of the psychometric functions, were seen with fewer errors.

5) Each observer produced more errors in the first 125 trials than the last 125 trials.

6) Unexpectedly, standard contrast showed a strong effect on the errors; as the standard contrast increased, the number of errors decreased.

Chapter 9. Comparison Between Electrophysiological and Psychophysical Measurements

We have determined that latency and amplitude of the ERP vary as a function of the contrast difference between a frequent and a rare stimulus; and, that P3 latency, regardless of electrode site, shows this relationship best.

This section discusses the similarities and the differences between the ERP and psychophysical results.[14]

Differences

The ERP-JND was larger than the difference limen obtained in the forced-choice paradigm. The minimum amount of contrast that an observer required to elicit a P3 was greater than the contrast corresponding to 95% correct on each psychometric curve. In addition, the psychophysical ΔCs and the ERP ΔCs were not parallel; at 5% standard contrast, the ΔCs differed by M = 2.3%, while at the 50% standard contrast, the amount of contrast between the ΔCs was M = 3.93%. In terms of Weber's ratios this difference decreased from $\Delta C/C$ = .4667 at 5% to $\Delta C/C$ = .0786 at 50%. These relationships are

[14] The ERP-JNDs of the electrophysiological study refer to the lowest ΔC/Cs that produced evident P3 waveforms at each contrast level of the frequent stimulus. In the psychophysical study the $\Delta C/C$ and JND are the same; $\Delta C/C$ is used in some of the figures.

displayed in Figures 39, 40 & 41, which show the ΔCs and the ΔC/Cs derived from both studies plotted as a function of the standard contrasts. Apparent in these plots is that ΔC as a function of the standard contrast is positive, whereas ΔC/C as a function of the standard contrast is negative. These relationships were found in both studies. A positive relationship was expected when the ΔC was plotted as a function of the standard contrast, however, the negative relationship obtained when ΔC/C was plotted as a function of the standard contrast was not expected. The ΔC/C has been shown to remain constant over medium contrast levels, and increase only at low standards (Gescheider, 1976). These data showed that ΔC/Cs decreased linearly from 5% standard contrast to 50% standard contrast. In addition, the functions obtained from the ERP measures were steeper than those obtained from the psychophysical measures.

The higher ERP-JNDs could have been due to the nature of the studies: i.e., the instructions given to the observers. In the ERP study the observers were instructed to count the rare stimuli, and they were told that the rare stimulus would be either a higher or a lower contrast. In the psychophysical study the observers were forced to choose a higher (or lower) contrast. At the end of each two-interval trial a choice had to made, and in many instances the observers believed they were guessing. The 2AFC paradigm "drives" an

Text continues on page 181.

Figure 39. (Top) Plots which compare the ΔC obtained in both studies as a function of the six standard contrasts.

The slopes of the functions are: ΔC ERP = .428, and ΔC 2AFC = .025

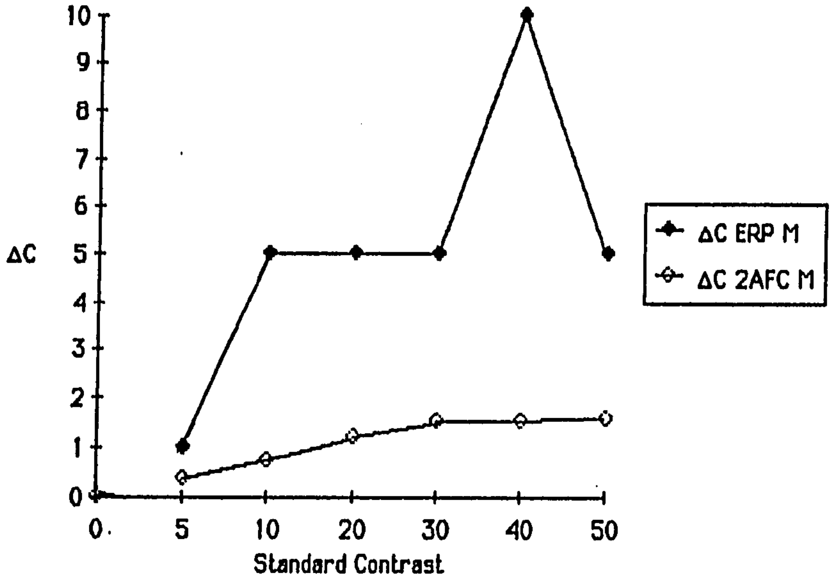
(Bottom) The $\Delta C/C$ obtained from both studies plotted as a function of the six standard contrasts.

The slopes of the functions are: $\Delta C/C$ ERP = -.0045,

$\Delta C/C$ 2AFC = -.001

These responses were from observer M.

Note: The distance between 5% and 10% standard contrast is shown equal to the distance between 10% and 20% standard contrast. This is an artifact of the computer.


10
9
8
7
6
5
4
3
2
1
0
ΔC
0
5
10
20
30
40
50
Standard Contrast
ΔC ERP M
ΔC 2AFC M

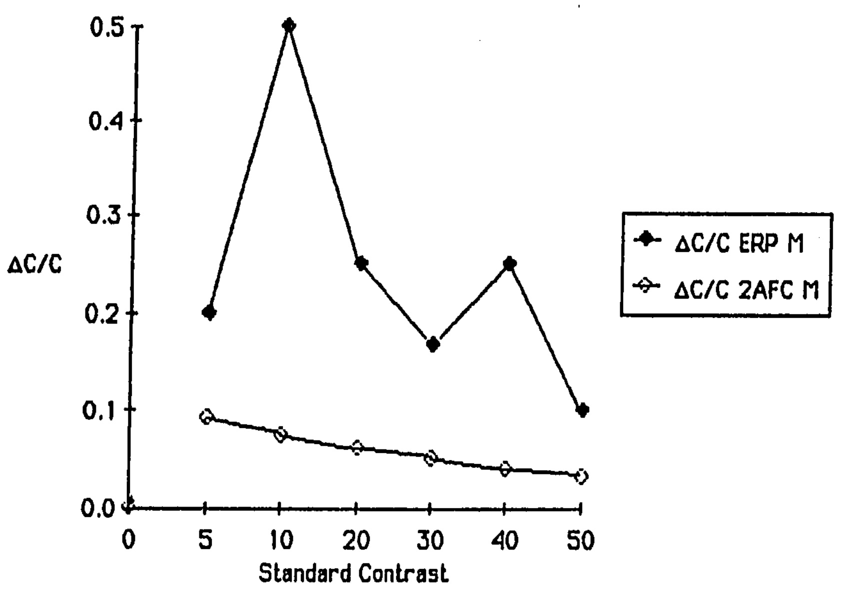
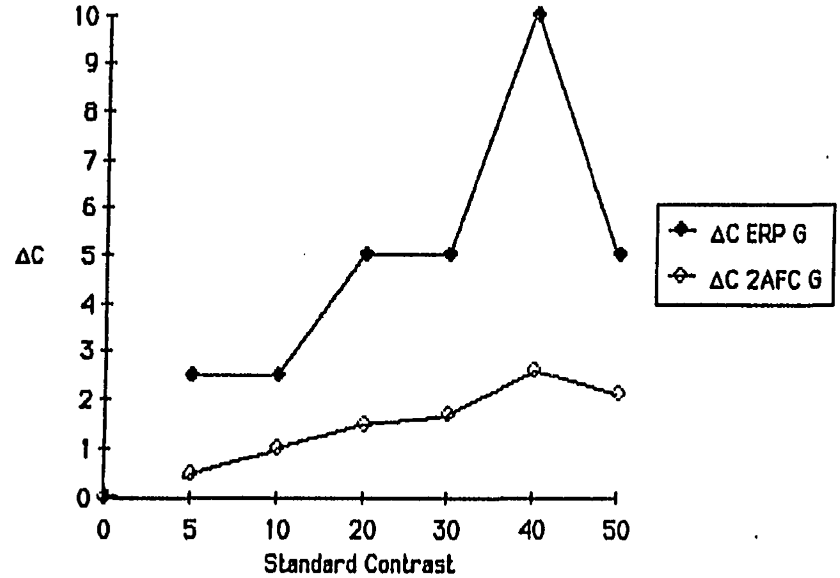

0.5
0.4
0.3
0.2
0.1
0.0
ΔC/C
0
5
10
20
30
40
50
Standard Contrast
ΔC/C ERP M
ΔC/C 2AFC M

Figure 40. (Top) Regression lines which compare the ΔC obtained in both studies as a function of the six standard contrasts.
The slopes of the functions are: ΔC ERP = .107 and ΔC 2AFC = .04

(Bottom) The $\Delta C/C$ obtained from both studies plotted as a function of the six standard contrasts.
The slopes of the functions are: $\Delta C/C$ ERP = -.006
$\Delta C/C$ 2AFC = -.001

These responses were from observer G.

Note: The distance between 5% and 10% standard contrast is shown equal to the distance between 10% and 20% standard contrast. This is an artifact of the computer.


10
9
8
7
6
ΔC
5
4
3
2
1
0
0
5
10
20
30
40
50
Standard Contrast
ΔC ERP G
ΔC 2AFC G

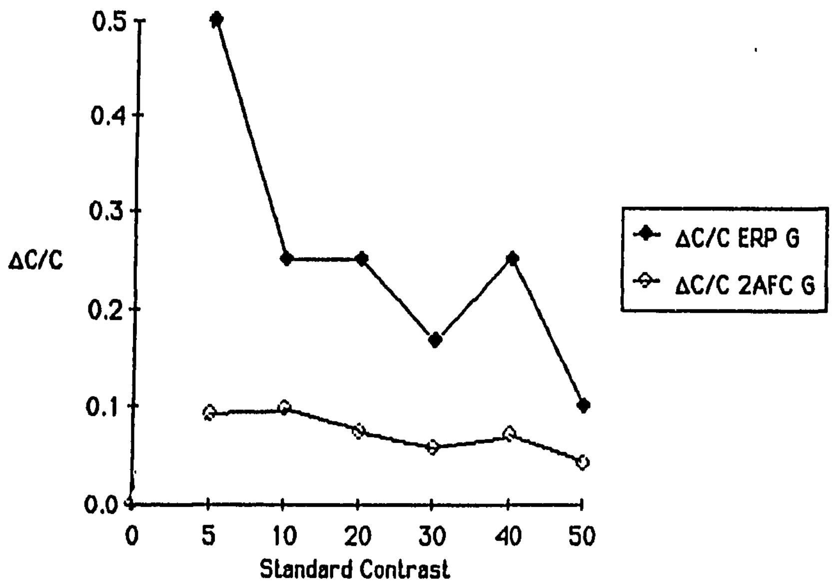
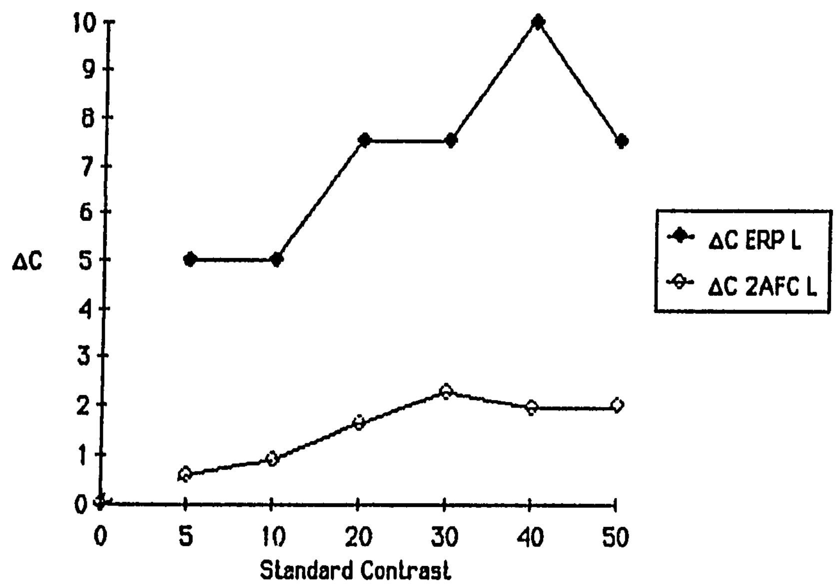

0.5
0.4
0.3
ΔC/C
0.2
0.1
0.0
0
5
10
20
30
40
50
Standard Contrast
ΔC/C ERP G
ΔC/C 2AFC G

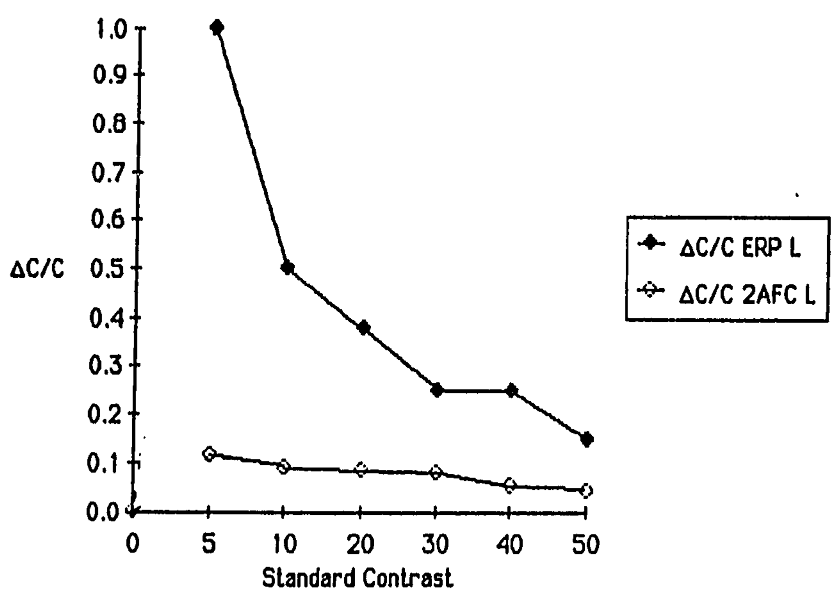
Figure 41. (Top) Regression lines which compare the ΔC obtained in both studies as a function of the six standard contrasts.
The slopes of the functions are: ΔC ERP = .08 and ΔC 2AFC = .033

(Bottom) The ΔC/C obtained from both studies plotted as a function of the six standard contrasts.
The slopes of the functions are: ΔC/C ERP = -.015
ΔC/C 2AFC = -.002

These responses were from observer L.

Note: The distance between 5% and 10% standard contrast is shown equal to the distance between 10% and 20% standard contrast. This is an artifact of the computer.


ΔC
10
9
8
7
6
5
4
3
2
1
0
0
5
10
20
30
40
50
Standard Contrast
ΔC ERP L
ΔC 2AFC L


ΔC/C
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
5
10
20
30
40
50
Standard Contrast
ΔC/C ERP L
ΔC/C 2AFC L

individual to respond, and is considered criterion free, whereas the criterion set by the observer in the ERP study was unknown.

Similarities

Analysis of the JNDs from both the psychophysical and electrophysiological studies revealed the same trend: as the standard contrast increased the JNDs and the variability around the means decreased.

The results appeared different when the dependent variable was the ΔC instead of the $\Delta C/C$. The minimum difference, between the frequent and the rare contrast required to elicit a P3, did not increase systematically as the frequent contrast increased. The amount of contrast between the frequent and the rare contrasts required for a P3 to be elicited remained the same at frequent contrasts of 20% and above (except at 40%). The ΔCs obtained in the psychophysical study for the standard contrasts 30% - 50% did not increase systematically either. This was demonstrated by the same degree of inclination of the slopes of the psychometric functions for these standard contrasts. The similarity between these two studies was also demonstrated by the slopes of the ΔC and the $\Delta C/C$ as a function of the standard contrast.

It appears that Weber's law does not hold for the results of either of these studies, in that $\Delta C/C \neq K$ (where K = a constant) which should result in a slope of zero when the $\Delta C/C$ is plotted as a function of the standard contrast. Bodis-Wollner, Hendley and Kulikowski (1972) investigated the JND of contrast discrimination using 6 c/d sinusoidal grating patterns, and found that Weber's law did not hold for these patterns either. However, for a 10 c/d grating pattern, Weber's law did hold for contrast discrimination (Bodis-Wollner, Hendley & Kulikowski, 1972; Campbell & Kulikowski, 1971). One simple equation does not fit these data.

The log/log plot of the $\Delta C/C$ obtained in both studies plotted as a function of the standard contrasts had negative slopes (Figure 42). Correspondence between the two studies was also shown by the positive relationship of the ERP-JND plotted as a function of the JND; $r = .789$, $t(34) = 7.49$, $p < .001$ (Figure 43).

Standard contrast showed a significant effect in both studies, in the ERP study the slopes of the regression lines which described latency and amplitude as a function of the ΔC varied with the frequent contrast. Steeper slopes described the ERP measures versus the ΔC at higher contrasts. In the psychophysical study, the slopes of the psychometric functions also varied with the standard contrasts, shallower slopes were produced at the higher standard contrasts.

Summary

In summary, there were four major conclusions regarding the relationship between the two studies. The first was that the

Text continues on page 187.

Figure 42. Log/log plot of the JNDs obtained in both studies as a function of the standard contrast.

Top - The ERP-JND plotted as a function of the frequent contrast.

Bottom - The JND obtained in the psychophysics study plotted as a function of the standard contrast.

Each data point is the mean of the three observers.

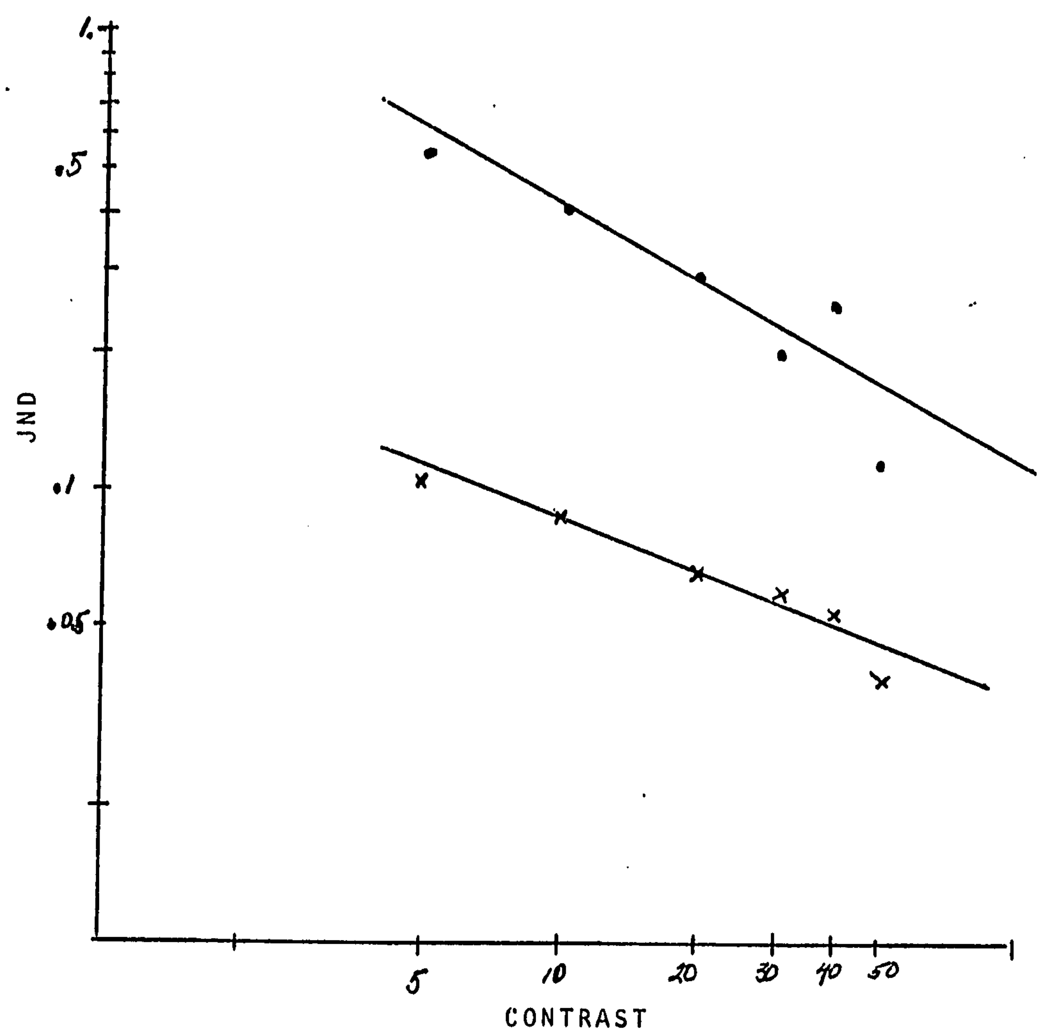
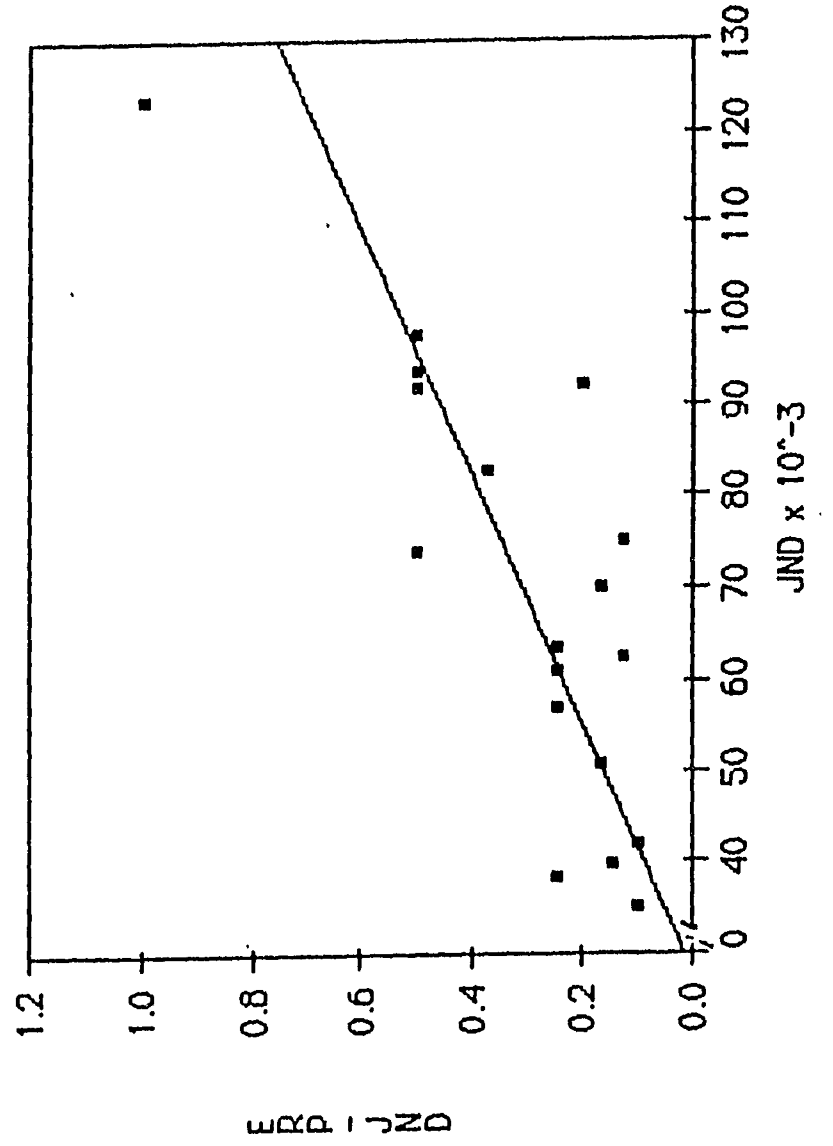

1.
.5
.1
.05
JND
5
10
20
30
40
50
CONTRAST

Figure 43. The ERP-JNDs(10^3) plotted as a function of the the JNDs obtained in the psychophysical study. The psychophysical JNDs are the means of the three observers.

Pearson Product-moment correlation: $r = .789$, $t(34) = 4.857$, $p < .001$.


1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
40
50
60
70
80
90
100
110
120
130
JND x 10^-3

ERP-JNDs were greater than the psychophysical JNDs. The second was that in both studies, as the standard contrast increased the JNDs and the variability around the means decreased. The third conclusion was that Weber's law did not hold for either of these studies. One simple equation does not describe the results of these studies. The final conclusion was that it appears that contrast discrimination between sinusoidal grating patterns of the same spatial frequency and luminance follows its own law, and this law applies to both ERP studies and psychophysical studies.

Chapter 10. Discussion

An Overview of the ERP Data

The results of this investigation demonstrated that changes in P3 latency and amplitude reflect visual discrimination processing. We demonstrated that latency and amplitude of the ERP vary as a function of the contrast difference between two stimuli that are identical in every parameter but contrast.

The data are consistent with Donchin and Isreal's (1980) assertion that P3 latency provides a measure of the time it takes to categorize events. (We can assume that the frequent and the rare stimuli fall into two distinct categories.) As the differences in intensity between the frequent and the rare stimuli became smaller, the ability to discriminate between the two stimuli became difficult, therefore the events took longer to categorize. On the other hand, as discrimination became easier the latency of the P3 reduced linearly as the contrast between the frequent and the rare stimuli increased.

In addition to the latency changes seen in the P3, N2 latency also varied, and was dependent on the contrast difference between two stimuli: as the amount of contrast between the frequent and the rare stimuli increased, the N2 latency decreased. The N2 observed in this study may be a component of the negative-positive wave complex

"N2-P_{3b}" described by Squires, Squires and Hillyard (1975b) and Snyder and Hillyard (1976), since N2 latency varied with P3 latency and was elicited at the same electrode site. In each instance, when a P3 was elicited, it was preceded by a N2. However, the correlation between N2 latency and P3 latency was somewhat larger between electrode sites (r = .743) than within electrode sites (r. = .692).[15]

N2 is best seen with the omitted stimulus or in subtracted waveforms that remove the P2 from the rare trace (Ritter, Simson, Vaughan & Friedman, 1978). This was not true for this study, since there was no difference between the summated and the subtracted waveforms in the amplitude or latency of the N2. Several of the ERPs in this study showed an exogenous positive deflection (P2?) in both the frequent and the rare traces that preceded N2 (Appendix B).

Näätänen and Michie (1979) suggested that N2 varies as a function of discrimination difficulty. They proposed that this component reflects task relevance as well as the combination of features that define the relevant stimulus, as opposed to the features in the stimulus which are to be ignored. The nontarget is not

---

[15] In general, a negative deflection that occurs between 200 msec and 400 msec after stimulus onset, and elicited by visual stimuli, is maximally recorded from an occipital site (Harter & Previc, 1978; Ritter, Simson, Vaughan & Friedman, 1978). This negativity is greater to the rare target than the frequent nontarget.

irrelevant, since it must be noted and compared against the relevant stimulus. For instance, in this study, the irrelevant stimulus could not have been ignored for two reasons: 1) the observer was told to fixate the center of the stimulus display in order to eliminate eye movement artifacts, and 2) to guarantee that the stimuli was seen and processed. Once the decision was made that the stimulus was not to be counted, then the P3 was either not elicited or had a low amplitude; this was not necessarily true for N2. As can be seen in Appendix B the N2 component was present for all of the frequent as well as the rare traces for one observer (G), implying that this observer was orienting to both stimuli, relevant and irrelevant; yet, this observer did not process the stimuli further after deciding the stimulus was irrelevant, since there was no evidence of a P3 to the irrelevant stimulus.

Three questions arise regarding N2: 1) Since the N2 was most apparent in the rare traces and occured at the same electrode site as the P3, is it indeed the same as the N2-P3b complex described by Squires, Squires & Hillyard (1975b)? 2) Is it merely the onset of the P3? It appears likely not to be the onset of the P3, since there is an obvious negative going deflection prior to the N2 peak. 3) Does the N2 reflect different processes when probabilities are varied? As seen in Chapter 6, the latency of N2 did not vary with the latency of P3 when the *a priori* probability of the target stimulus occurrence was greater than .5.

The amplitude, as well as latency, reflected contrast differences between the two stimuli. The amplitude of the response increased as the amount of contrast between the frequent and the rare stimuli increased. A positive relationship was obtained between the amplitude and the difference in contrast (ΔC). However, the results of the statistical analyses indicated that discrimination processes were reflected more in P3 latency than amplitude. This may be due to the nature of the amplitude measurement, which is supposed to reflect subjective probability of the eliciting event (Duncan-Johnson & Donchin, 1977). The probability of the occurrence of the rare event remained the same for all of the conditions in this study (9:1), with the exception which was discussed in Chapter 6. The subjects were aware of the stimulus probability since they were experienced in the lab.

P3 Threshold

At the P3 discrimination threshold (the smallest contrast difference between two stimuli that elicited a P3) the stimulus may become ambiguous; and one can ask whether false alarms occurred. Due to the nature of the task this study, a positive statement cannot be made of whether or not they occurred. However, we can assume false alarms did not occur because the smallest contrast differences between the frequent and the rare contrasts necessary to produce a

P3 fell above 95% correct on the psychometric curves, and the observers gave accurate counts of the number of rare stimulus presentations whenever a P3 waveform was elicited.

A question arises, as to why there was such a difference between the contrast values for ERP and psychophysical JNDs. One possibility is that the difference between the JNDs obtained in the two studies may represent whether or not a full analysis of the stimulus occurred. The P3 reflects encoding, memory comparison and decision (Rösler, Sutton, Johnson, Mulder, Fabiani, Plooij-Van Gorsel & Roth, 1986) along with some kind of an internal feedback mechanism. In other words, the identification of the target and the emission of P3 requires a rather full analysis of the stimulus and a comparison against target representations in memory (Hillyard, Picton & Regan, 1978). The JND obtained in the 2AFC study may represent two of these information processing mechanisms, encoding and memory comparison while eliminating the feedback mechanism since the observer was forced into making a decision without internal or external feedback provided. We can assume that full analysis of the stimulus did not occur since feedback was not provided. When the observer was forced into a choice, it seems that the encoding and memory mechanisms were all that were necessary for a correct choice.

The Relationship Between Visual ERPs and Visual Psychophysics.

We have established that spatial contrast discrimination can be evaluated by ERP methods. Now, one can ask "Will ERPs replace psychophysics for evaluating suprathreshold contrast differences?"

To ideally answer this question the ERPs should be recorded during the psychophysical testing. For instance, ERP recording should start at the beginning of each of the two 500 msec intervals in the 2AFC study. The EEG for each target contrast would be routed to one of two channels, HIT or MISS, then the number of correct responses versus the number presented would enable a psychometric function to be derived. This would show the influence of forcing an observer's response on the latency and amplitude of the P3 in addition to obtaining a psychometric function.[16]

For experimental purposes, the methods used in this study seem to be more advantageous than simultaneous testing because: 1) a P3 was elicited to the rare stimulus and may not have been obtained with simultaneous testing because of the large number of target stimuli,

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[16] In the "2AFC-ERP" paradigm the *a priori* probability of the nontarget stimulus would be .5, there would be several target stimuli within each testing session, with the *a priori* probabilities of less than .1 for each of the target stimuli. Since the number of target stimuli presented within each session would be relatively large for a P3 study, one could question whether or not a P3 would be elicited.

2) two JNDs based on the same mean contrast were derived which were compared, and 3) the slopes describing the functional relationship of the ERP measures to the ΔC were examined. The stimuli were presented in a similar manner in the two studies. In the 2AFC study, there were 500 two-interval trials, in which the standard and the comparison stimuli were presented randomly. In the ERP study, there were 512 random presentations.

Hillyard, Picton and Regan (1978) discussed the problem of ERPs replacing psychophysics:

> . . . The measurement of sensory magnitude through behavioral techniques is difficult and controversial, and an early hope of EP research was that it might provide some means of evaluating sensory magnitude without the need for behavioral measurement. A great deal of early research thus attempted to correlate sensory EPs to the intensity of the evoking stimuli, in relation to one of the several psychophysical laws. There has been little success. Indeed the very concept that sensation can be adequately described in one-dimensional terms is questionable. (pp. 234-235).

In general, sensory EPs have thresholds that are near or slightly above behavioral threshold. The authors referred to the sensory locked exogenous potential that occurs within 10 msec for the auditory modality, 50 msec for the somatosensory modality and around 100 msec for the visual modality, and recorded from the scalp near the primary sensory cortex. Studies investigating the endogenous ERP to the intensity of the evoking stimuli in relation to one of the several psychophysical laws is lacking in the literature. The results of this investigation indicated that the threshold measures of neither of these studies strictly followed a psychophysical law.

A Comparison with Other Studies.

The shape of the ERP traces obtained in this study resembled those obtained in other visual paradigms (Friedman, Vaughan & Erlenmeyer-Kimling, 1980, p. 118).[17] These results are consistent with previous P3 studies, in that the latency of the visual P3 (450 msec) occurs about 100 msec later than the latency of the auditory P3 (350 msec) (Squires, Donchin, Squires & Grossberg, 1977). The mean P3 latencies elicited by the observers in this study were 454 msec.[18]

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[17] The traces seen in Friedman, et al., (1980) were averaged after the removal of EOG artifacts.

[18] Since the negativity recorded in this study occured at about the same latency as the auditory P3, while the visual P3 occured around the same latency as the auditory N400, one might consider that the endogenous ERPs seen in one modality might show a reversed polarity in the other modality. Although, this is not likely, since the same electrode sites are used for P3 studies in both modalities.

Studies have reported that larger amplitudes at the P_Z electrode are seen to the rare visual stimulus (Mullis, Holcomb, Diner & Dykman, 1985). Simson, Vaughan and Ritter (1977) found that the maximum P3 amplitude was recorded at the P_Z electrode site to both auditory and visual rare stimuli. However, Snyder, Hillyard & Galambos (1980) recorded maximum P3s at the vertex for auditory, visual and somatic stimuli. (The vertex is basically the same as Z_{63}, the vertex (Z_{50}) is just posterior to the Z_{63} electrode site.) In the present study, two observers elicited larger P3 amplitudes at the P_Z site; and the third observer at the Z_{63} site.

The Stimulus

Loveless (1983) concluded that the P3 component depends less on the physical characteristics of the stimulus than on the psychological context in which it is presented. Indeed the P3 did occur because of it's relevance to the observer. However it's latency and amplitude changed because of some physical characteristic of the stimulus. In this investigation, the observers ability to discriminate the variation in one physical characteristic, contrast, resulted in reliable P3 waveforms that varied as a function of contrast. In addition, Schechter, Callaway, Halliday and Naylor (1986), investigated the effect of another single characteristic, spatial frequency, of sinusoidal grating patterns on P3 latency and reaction time (RT). Their results showed that spatial frequency had the same effect on both RT and P3 latency, faster RTs and earlier P300s occurred with low spatial frequency (0.8 c/d of visual angle) versus the high spatial frequency, 8.0 c/d.[19] Therefore, the variation in one physical characteristic of a simple visual stimulus was all that was required for an observer to elicit a P3.

Sinewave grating patterns are the simplest visual stimuli, in that they can be used through Fourier synthesis to build up any complex object. Sinewave grating patterns have been used extensively to study the imaging capacity of the eye (Campbell & Green, 1965), and single visual neurons (Enroth-Cugell & Robson, 1966). Most other types of stimuli, when passing through the eye are changed because of blur and scatter. The sinewave pattern is imaged as a sinewave pattern on the retina, blur and scatter cause only a loss of contrast (Shapley & Lennie, 1985). The sinewave is one-dimensional and contains one frequency. A single spatial frequency, 2.3 cycles per degree of visual angle, was used in this

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[19] These authors did not discuss the primary visual evoked potential, which is known to be effected by spatial frequency in the same manner as their obtained results. The P100 of the VEP occurs earlier with low spatial frequencies (Parker & Salzen, 1977).

study. Using one spatial frequency involves one channel from the retina to the visual cortex (Shapley & Lennie, 1985).

Thus, we feel we were able to evaluate an observer's sensation without the confounding effects of conceptual (i.e., specific cognitive or semantic) differences between the stimuli.

Anatomy and Pharmacology

The primary visual evoked potential to full field grating patterns is recorded maximally from about 5 cm. above the inion, which is directly over the primary visual cortex. Signals arising from retinal cells travel via axons to the lateral geniculate nucleus (LGN) of the thalamus, which is where visual processing is said to begin (Carpenter, 1978), and then the LGN projects to the primary visual cortex.

However, the origin of the P3 in a visual paradigm is still unresolved. Intracranial recordings have been studied in patients undergoing neurosurgery in the brain areas that have been implicated as being the source for the P3. The cortex (Simson, Vaughan, & Ritter, 1977), the thalamus (Yingling & Hosobuchi, 1984, studied one chronic pain patient) and hippocampus and amygdala (Halgren, Squires, Wilson, Rohrbaugh, Babb & Crandall, 1980, studied 6 epileptic patients) have been implicated as areas that are the source for the P3 component. The epileptic patients were not simultaneously implanted with thalamic electrodes. And, the pain patient was not simultaneously implanted with hippocampal electrodes. If these patients were implanted with both thalamic and hippocampal electrodes and P3 was recorded, which, then would produce greater P3 magnitudes? Nevertheless, implanted electrodes are probably closer to the source of the P3 than scalp electrodes, and they are not subjected to the added resistance of the skull. In this study, the P3 latencies at P_Z occurred earlier, and showed a higher correlation to contrast differences than they did at the Z_{63} electrode; although this difference was not statistically significant. This could imply that in a visual P3 paradigm, the source of the P3 could be closer to P_Z than the vertex (P_Z is closer to the primary visual cortex than Z_{63}, however, P3s are not recorded at the O_Z site).

Follow-up Studies and Conclusions

The results of this investigation could lead to further studies which would explore:

1) Why a large difference between the electrodes was found for the N2 latency and does this difference between the sites relate to contrast differences? This could have occurred because visual stimuli were used in this study and P_Z is closer to the visual cortex.

2) Why was the same amount of contrast required, as the minimum

for a P3 to be elicited, when the frequent stimuli were 20%, 30% and 50%?

3) Why, when the frequent contrast was 40% was a larger contrast difference needed to elicit a P3? This result could merely be because of the small number of observers tested; however, the results appeared consistent.

4) One should explore the effect of randomizing the frequent stimulus, rather than the rare stimulus within a session, on latency and amplitude of the ERP.

In conclusion, it can be asserted with the present evidence that (1) cognitive or semantic differences between stimuli were not necessary for an observer to elicit a P3. (2) Subjective *a priori* probabilities were not necessary for peak-to-peak amplitudes to vary. (3) The latencies of N2 and P3 decreased and their amplitude increased as the observers were more certain of their discriminations. 4) The frequent contrast had an effect of the ERP measures in this study. This may have occurred because only one frequent contrast was presented within each testing session. 5) Within one testing session, it appeared that the observers maintained a memory representation of the level of the frequent contrast against which the comparisons were made. 6) Sensitivity levels to visual stimuli corresponded between psychophysical studies and electro-physiological studies. 7) In addition, we have also shown that in a visual paradigm, where a visual fixation point is used, and both the frequent and the rare stimuli fall on the same retinal location, in normal observers, eye movements do not appear to confound the signal. This was demonstrated by the low artifact rejection rate.

This was the first ERP study that varied the contrast of sinusoidal grating patterns of identical spatial frequency, orientation and luminance around more than one frequent contrast, while psychophysical and ERP JND thresholds were obtained, as well as the functional relationships between the latency and amplitude of the ERP and the ΔC.

APPENDIX A

Signed and witnessed consent forms.

Principal Investigator Gloria L. Kass

Title of Project AN ELECTROPHYSIOLOGICAL AND PSYCHOPHYSICAL INVESTIGATION OF SPATIAL CONTRAST DISCRIMINATION IN HUMAN VISION

In each session the observer will view grating patterns produced by a Cathode Ray Tube (CRT). Several testing sessions will be required. During the sessions that will last about one hour each, the tasks of the subject will be to indicate which of two grating patterns appears darker or lighter. During the remaining sessions scalp electrodes will be used while viewing the grating pattern. Recording scalp electrode signals in response to sinusoidal grating patterns is a standard clinical procedure. The electrodes present no electrical shock hazards because of a special ground wire. The paste between the electrodes and skin is harmless as is the light level of the CRT display. It is not expected that the subject will experience any discomfort as a result of this procedure and no side effects have been reported.

Andrew Glover

PRINT NAME AND ADDRESS OF WITNESS

300 E 46th Street

New York City 10017

[illegible]

Signature of Witness

Name of Individual to be Studied

[illegible]

[illegible] 9/10/86

Signature of Investigator (date)

Principal Investigator Gloria L. Kass

Title of Project AN ELECTROPHYSIOLOGICAL AND PSYCHOPHYSICAL INVESTIGATION OF SPATIAL CONTRAST DISCRIMINATION IN HUMAN VISION

In each session the observer will view grating patterns produced by a Cathode Ray Tube (CRT). Several testing sessions will be required. During the sessions that will last about one hour each, the tasks of the subject will be to indicate which of two grating patterns appears darker or lighter. During the remaining sessions scalp electrodes will be used while viewing the grating pattern. Recording scalp electrode signals in response to sinusoidal grating patterns is a standard clinical procedure. The electrodes present no electrical shock hazards because of a special ground wire. The paste between the electrodes and skin is harmless as is the light level of the CRT display. It is not expected that the subject will experience any discomfort as a result of this procedure and no side effects have been reported.

Andrew Glover
PRINT NAME AND ADDRESS OF WITNESS
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NEW YORK CITY 10017
Andrew Glover
Signature of Witness

M. Piccahilardi
Name of Individual to be Studied

Gloria Kass 9/10/86
Signature of Investigator (date)

APPENDIX B

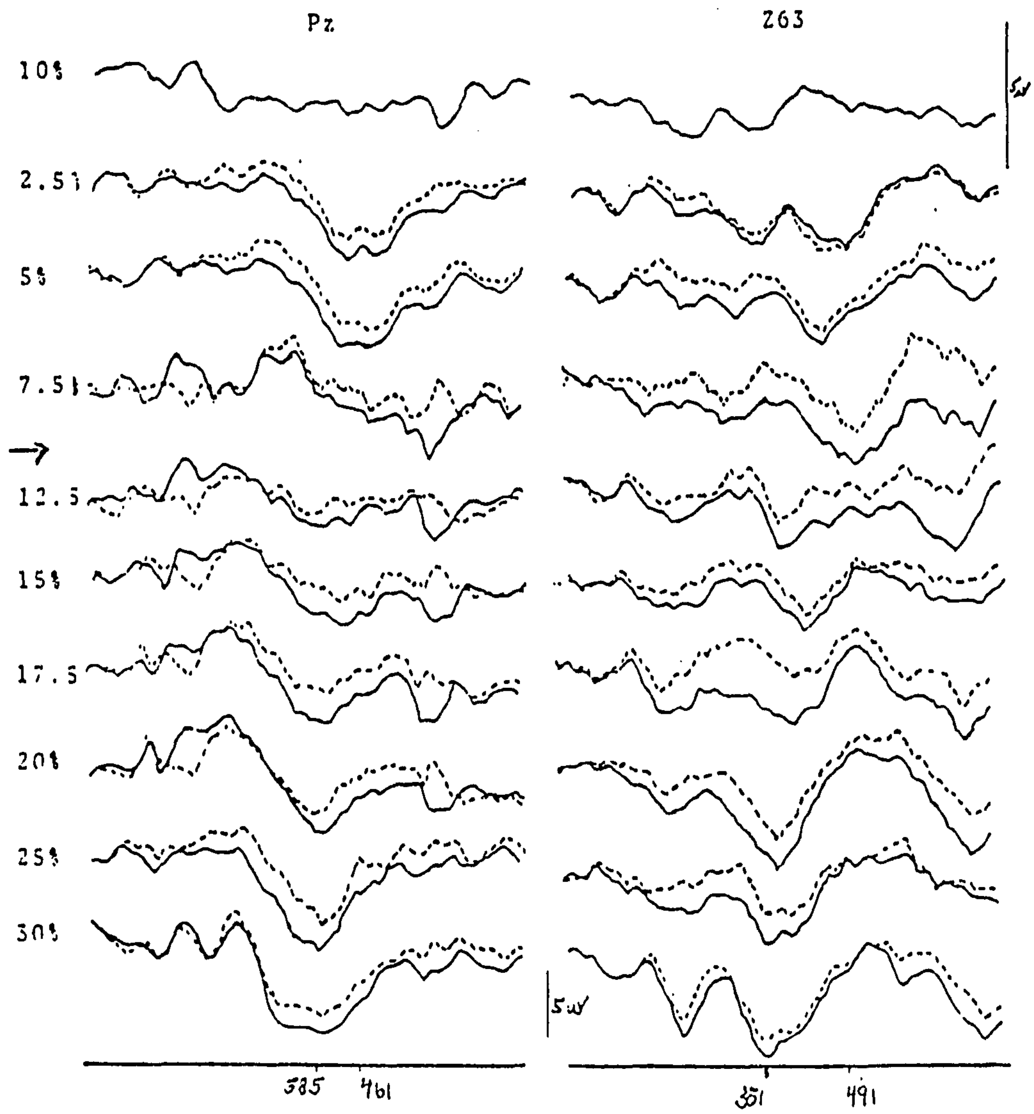
Traces evoked by the frequent and the rare stimuli.

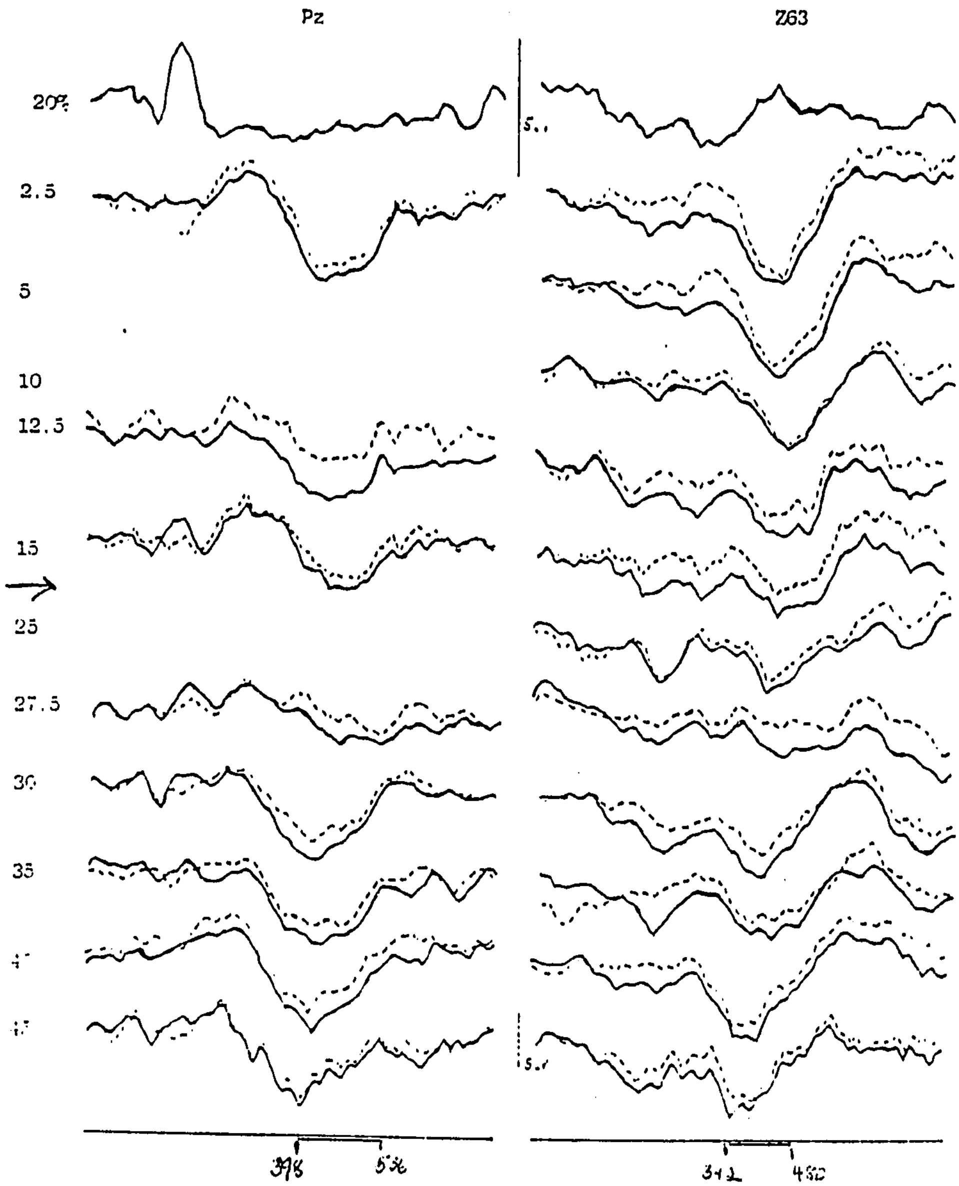
The arrows indicate where, in the sequence of the rare traces, the contrast of the frequent stimulus would fall.

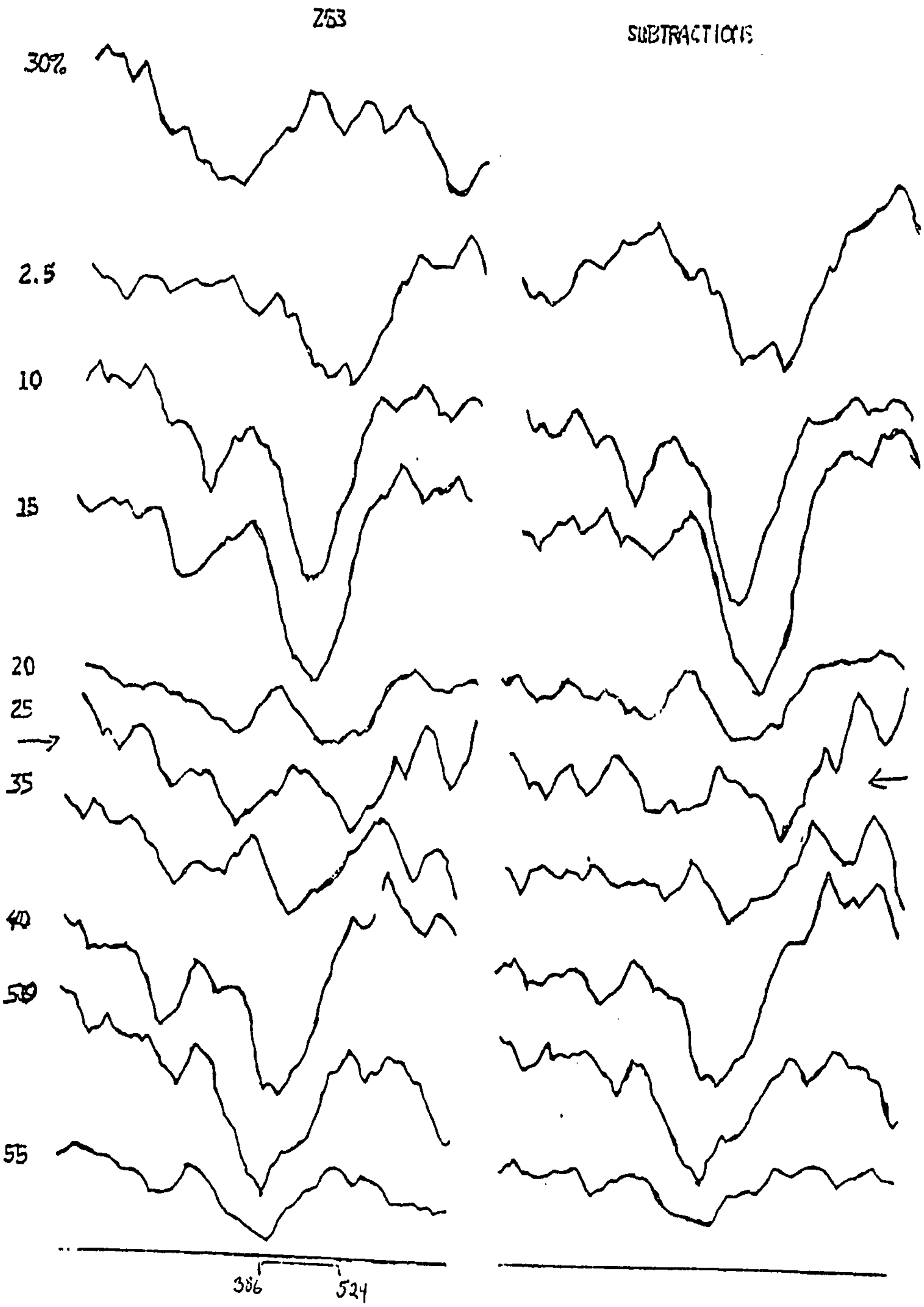
The length of each epoch is 768 msec.

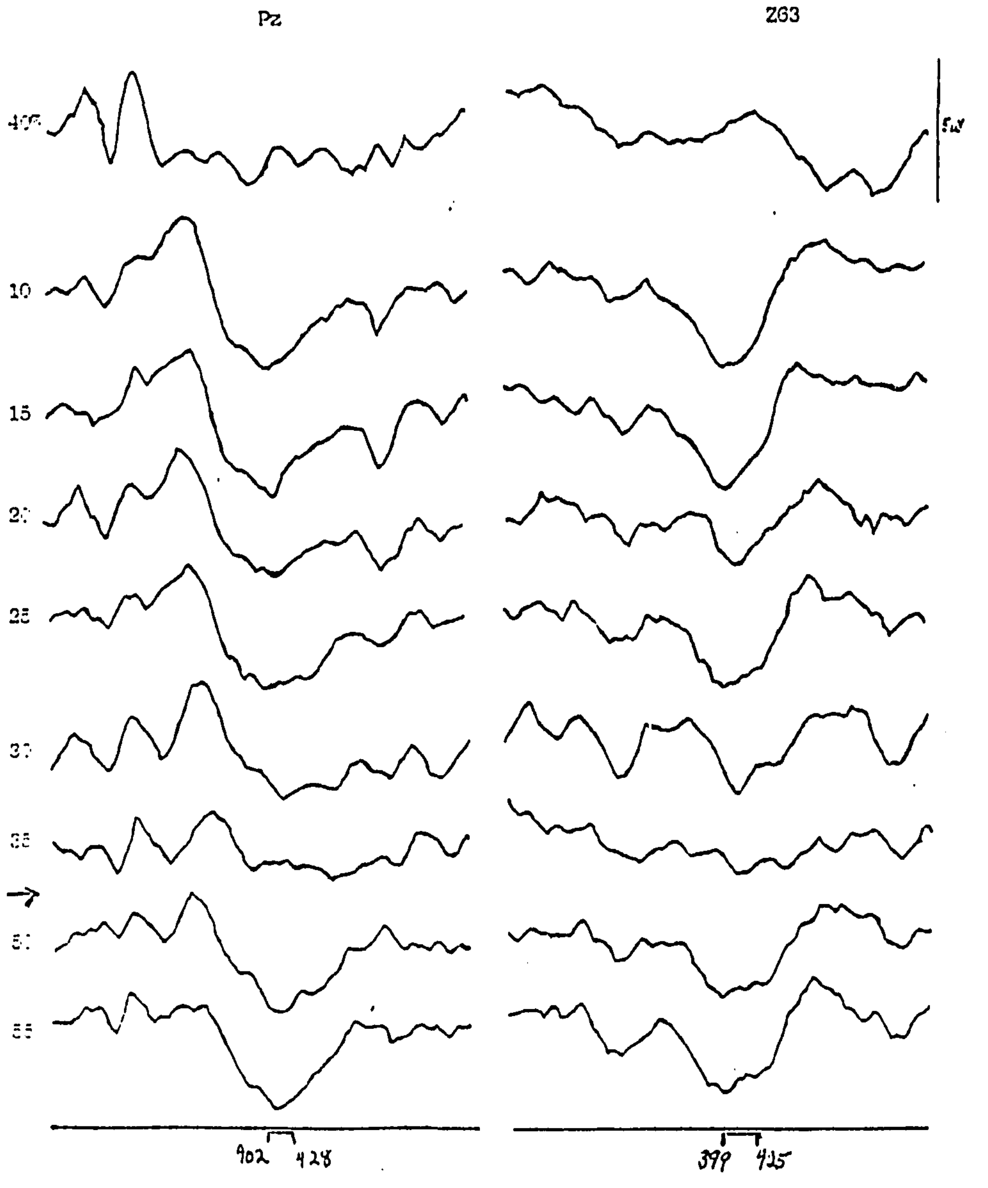
The calibrations for each set of traces are identical.

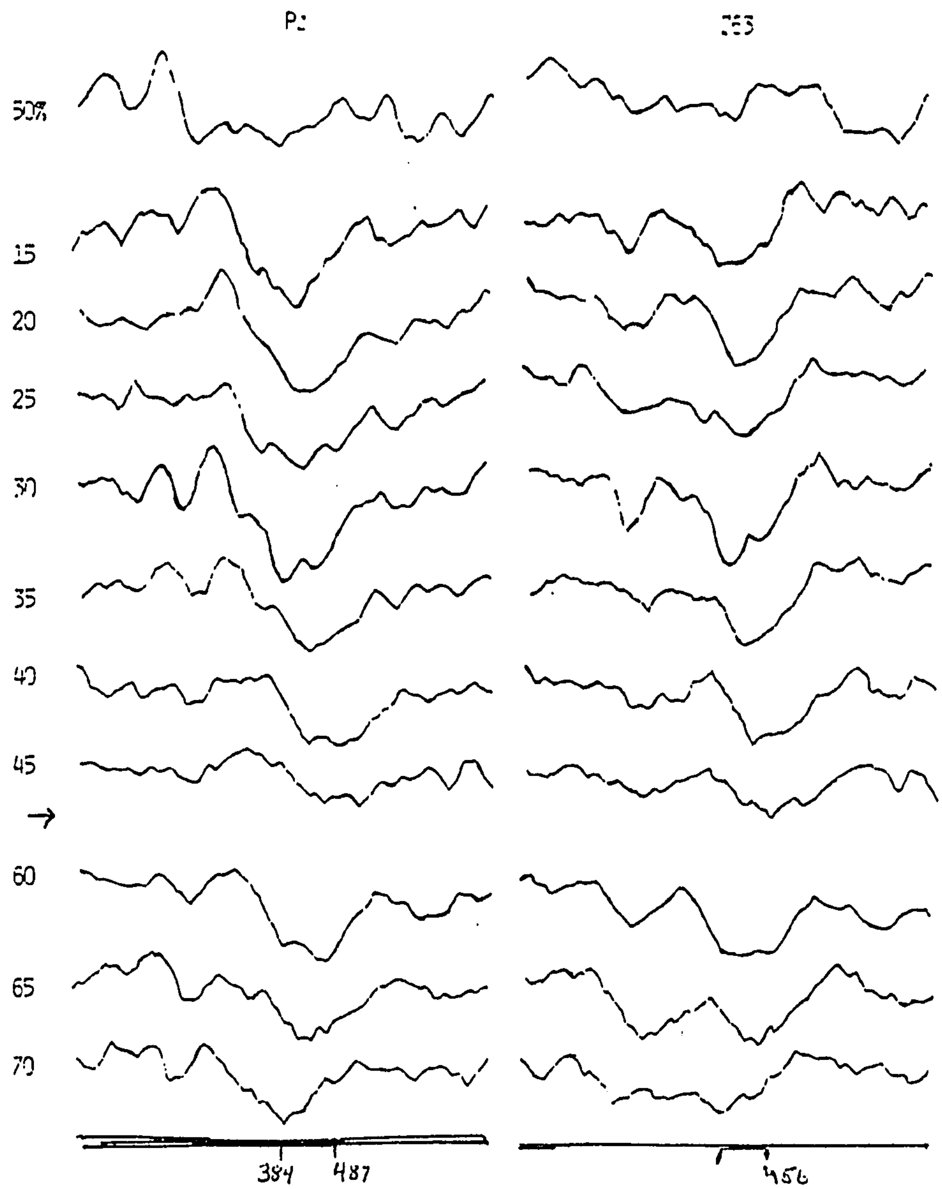
List of Waveforms

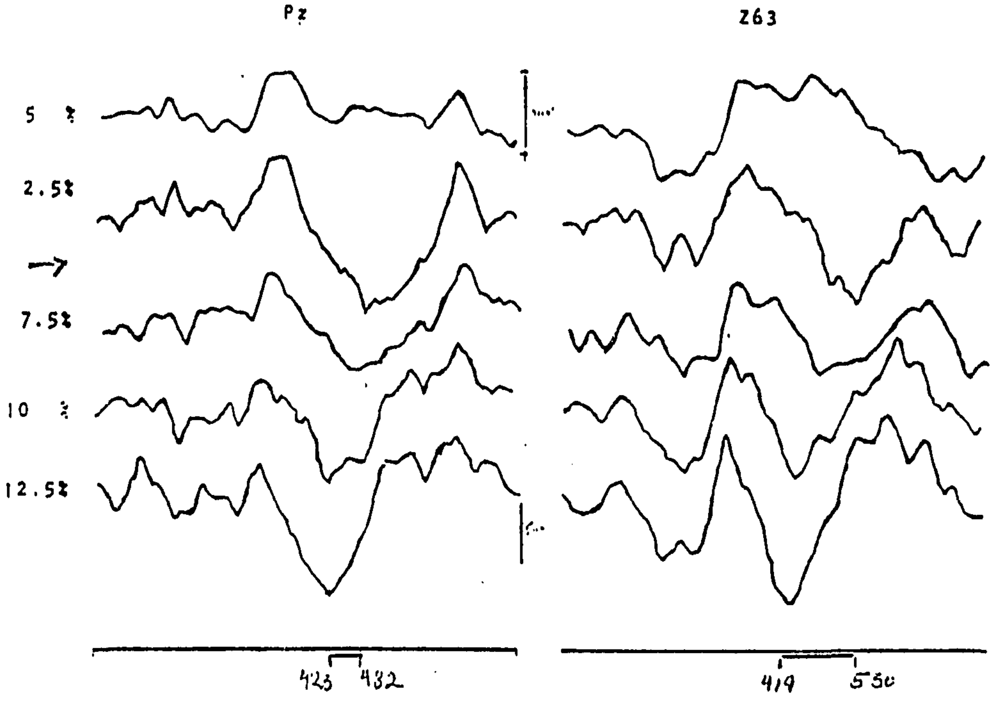

Pz
Z63
10%
2.5%
5%
7.5%
12.5
15%
17.5
20%
25%
30%
5uV
385
461
351
491

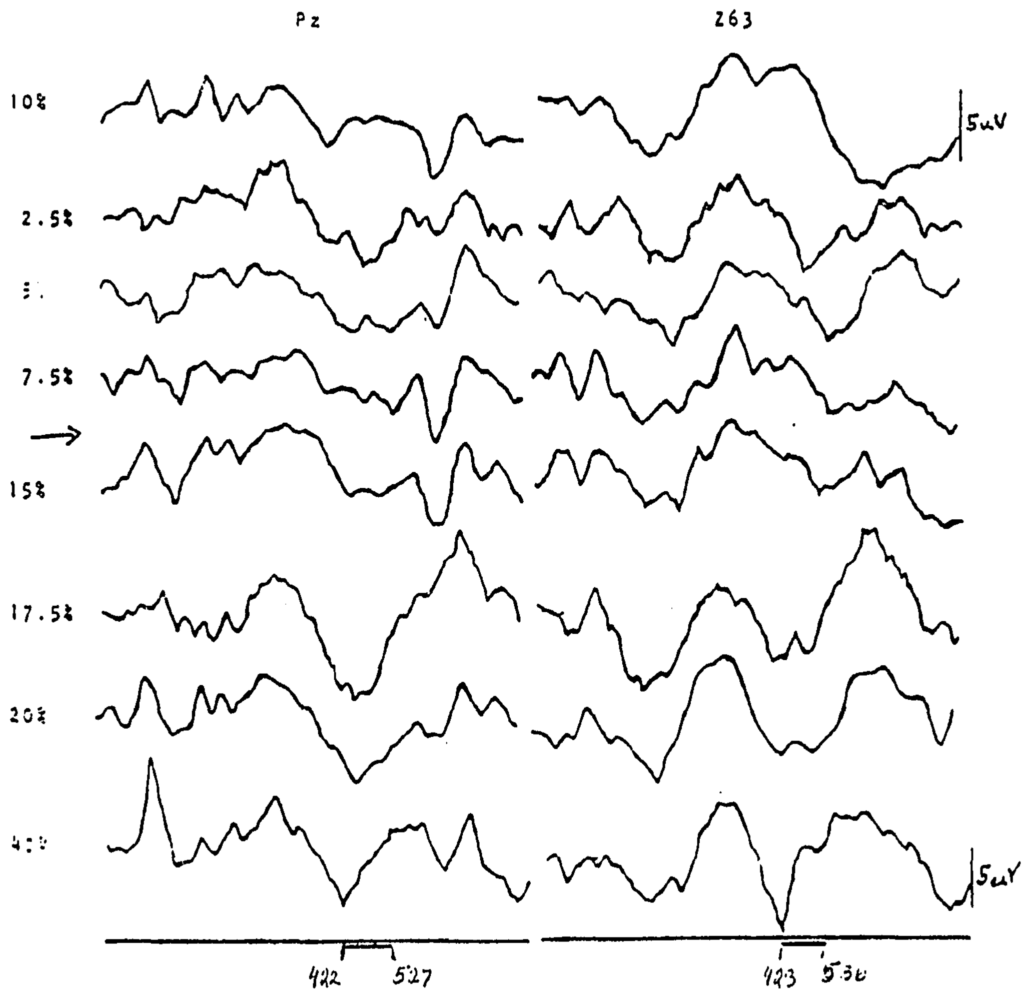

Pz
Z63
20%
2.5
5
10
12.5
15
25
27.5
30
35
398
536
342
480

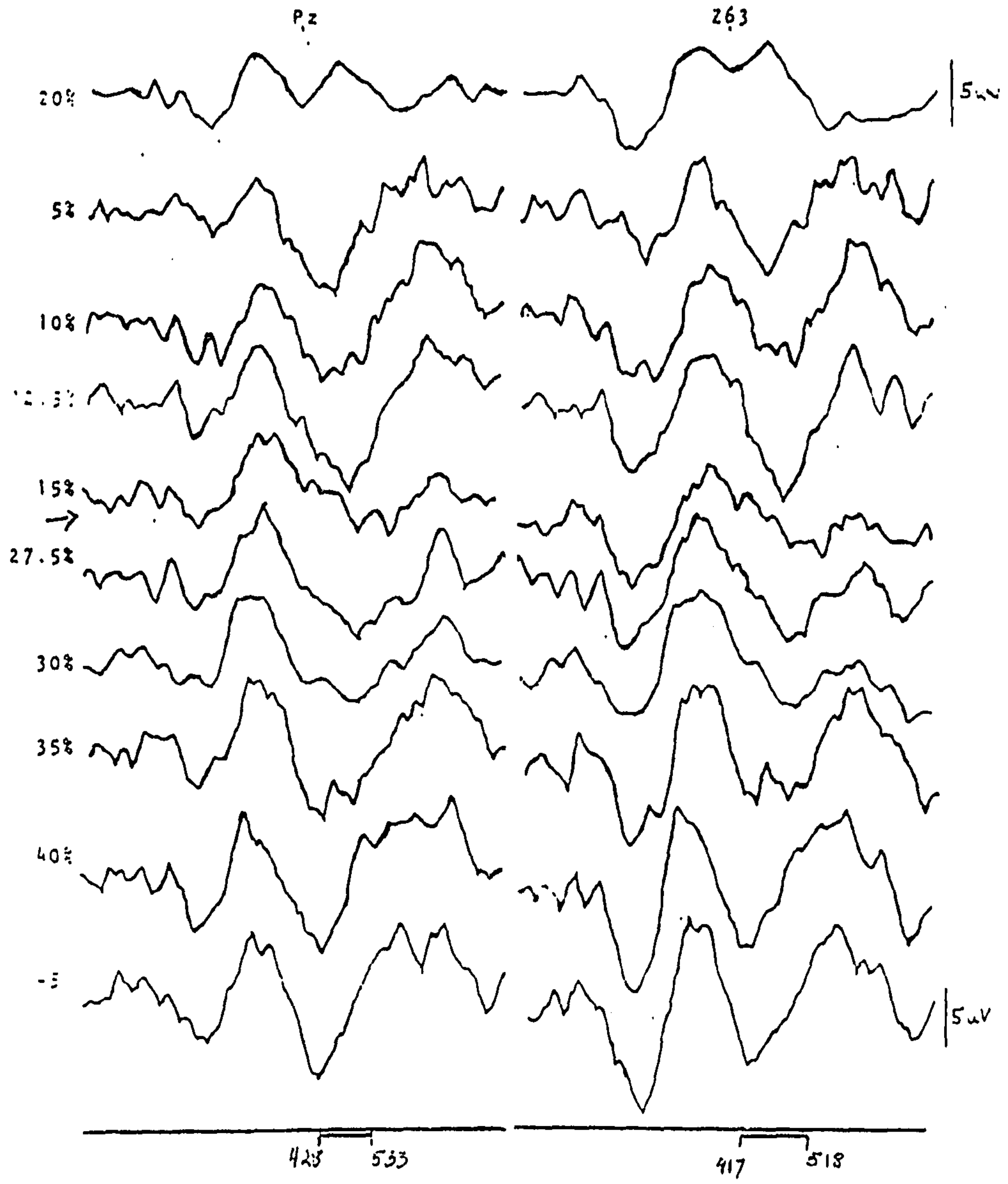

Z53
SUBTRACTIONS
30%
2.5
10
15
20
25
35
40
50
55
386
524

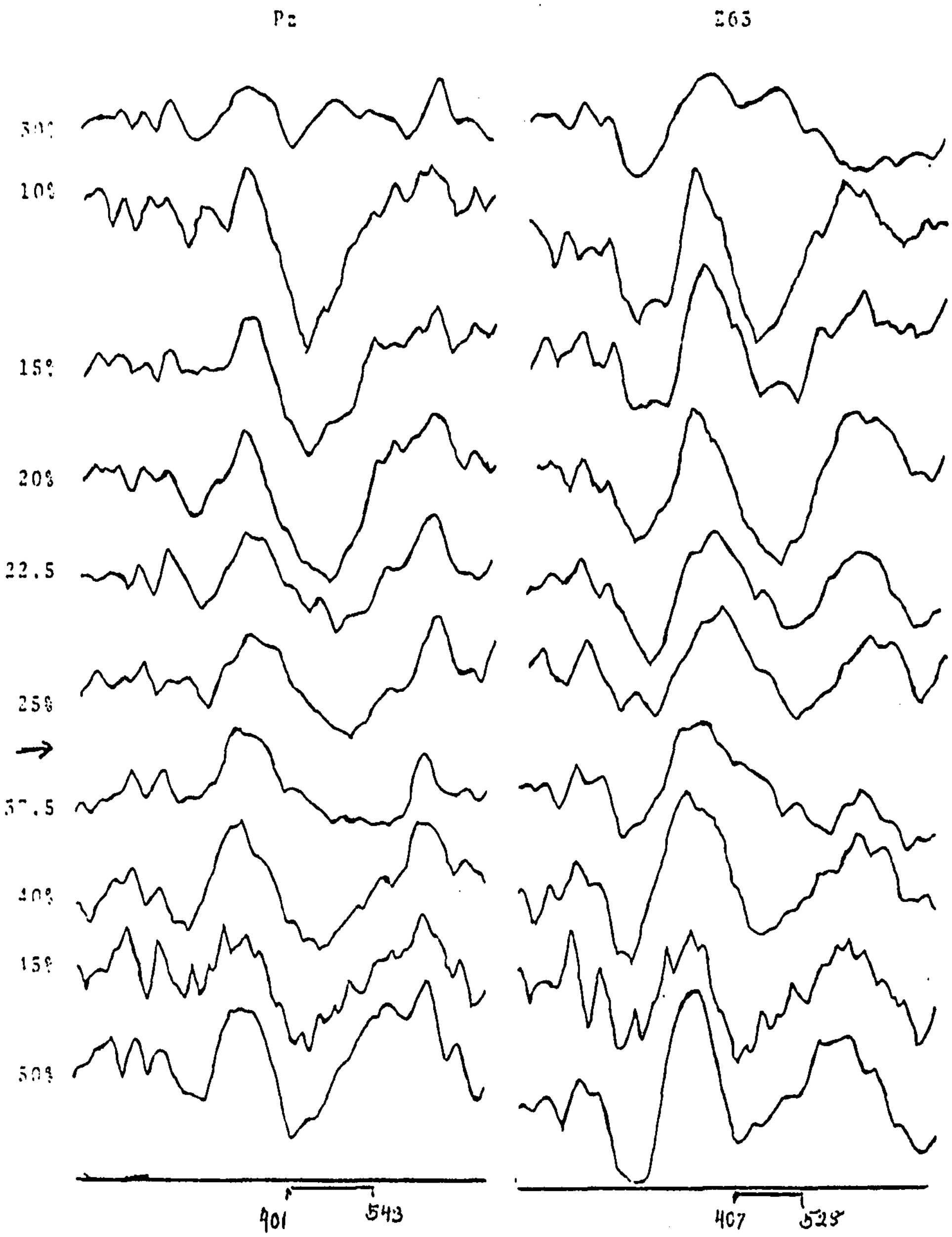

Pz
Z63
5uV
40
10
15
20
25
30
35
50
55
402
428
399
425

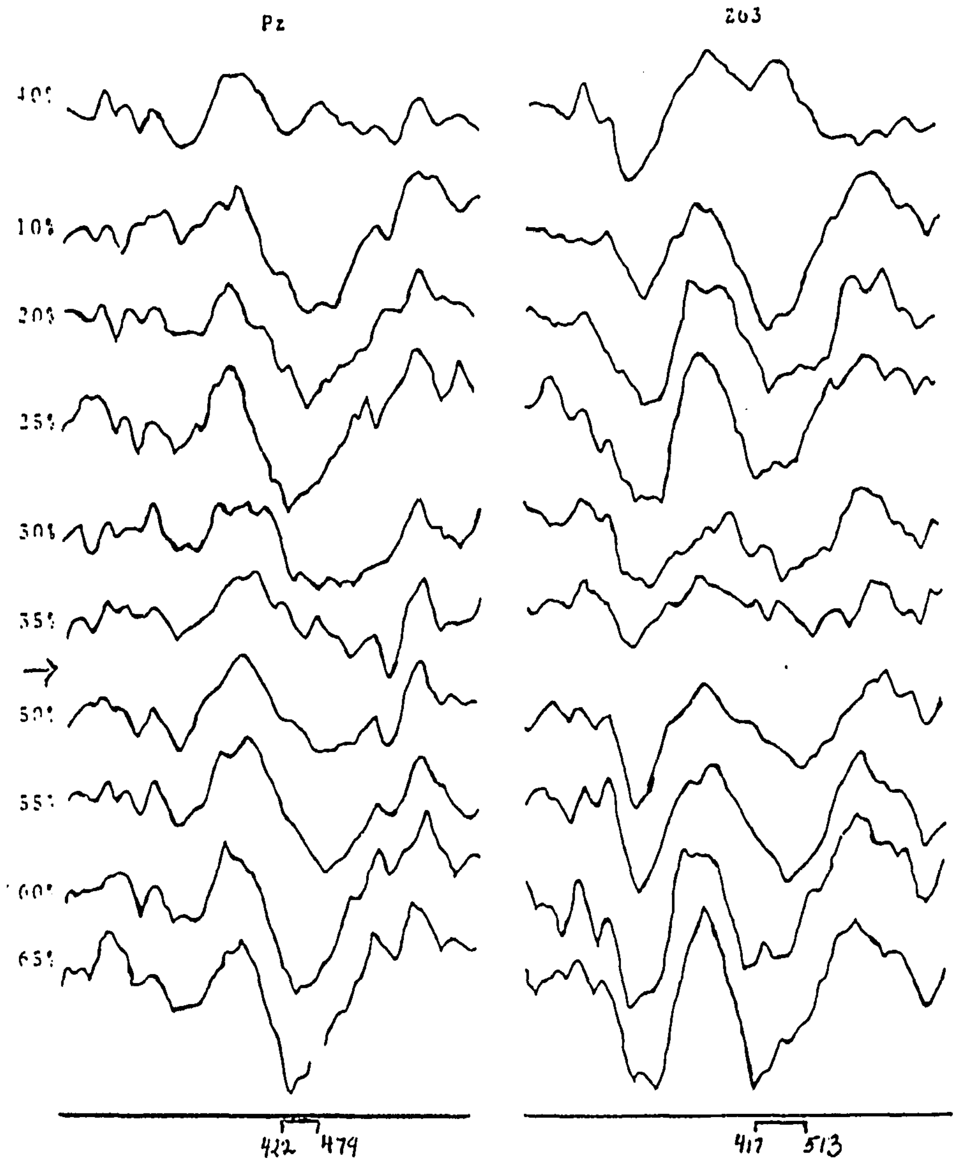

Pz
50%
15
20
25
30
35
40
45
60
65
70
384
487
456

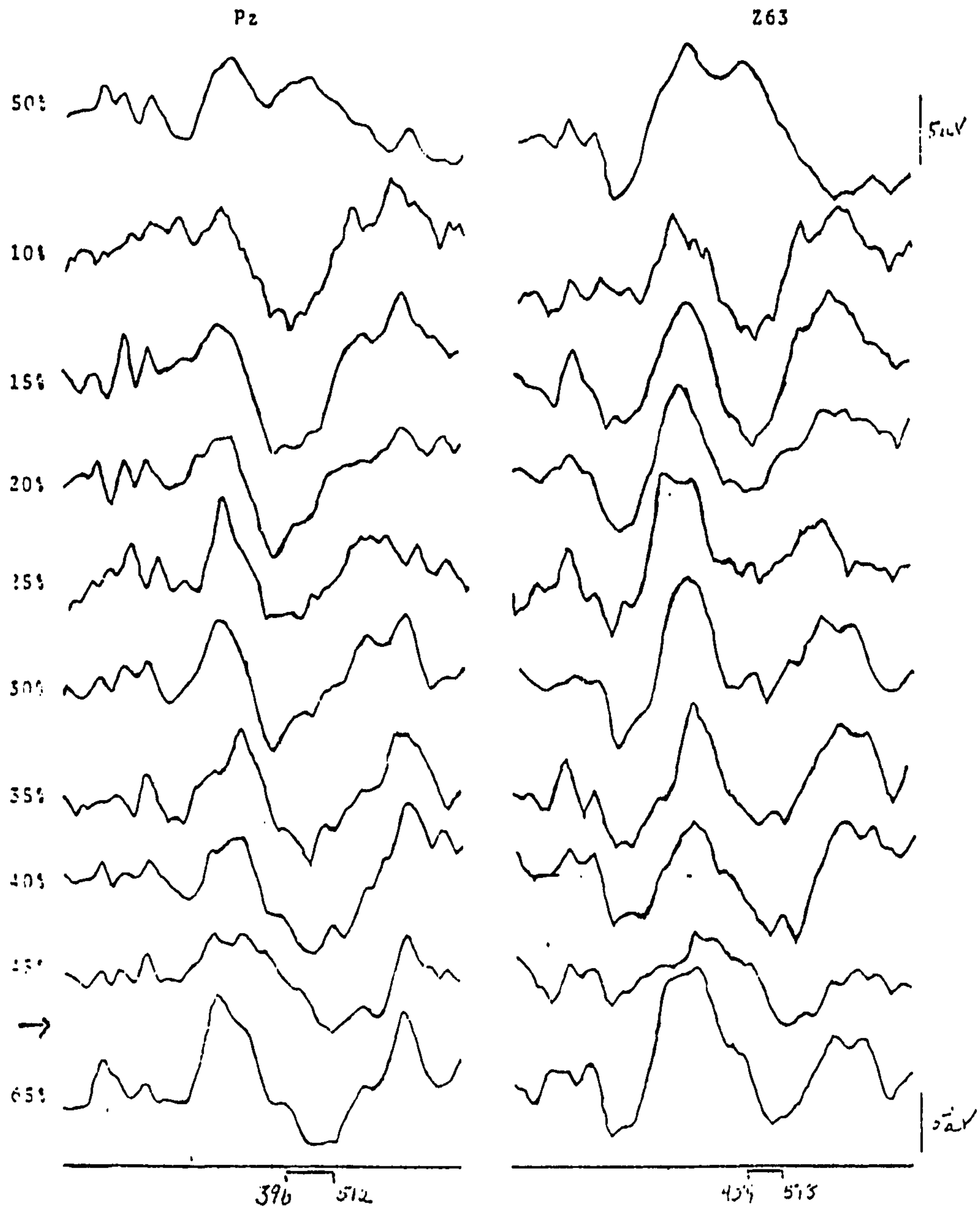

Pz
Z63
5 %
2.5%
7.5%
10 %
12.5%
423
432
419
550

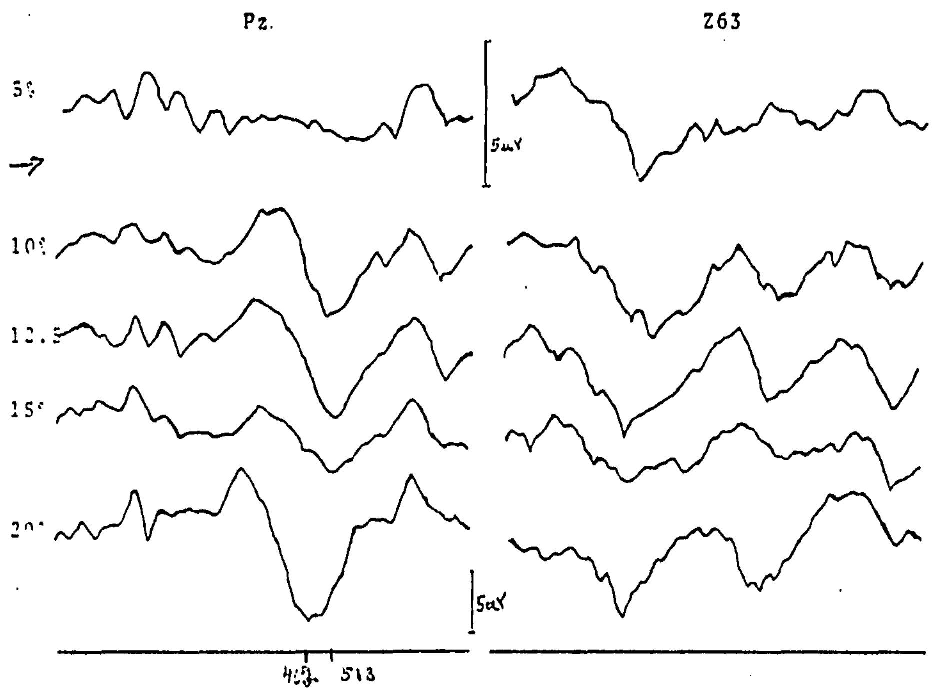

Pz
263
10%
2.5%
7.5%
15%
17.5%
20%
5uV
5uV
422
527
423


Pz
263
20%
5%
10%
15%
27.5%
30%
35%
40%
5µV
423
533
417
518

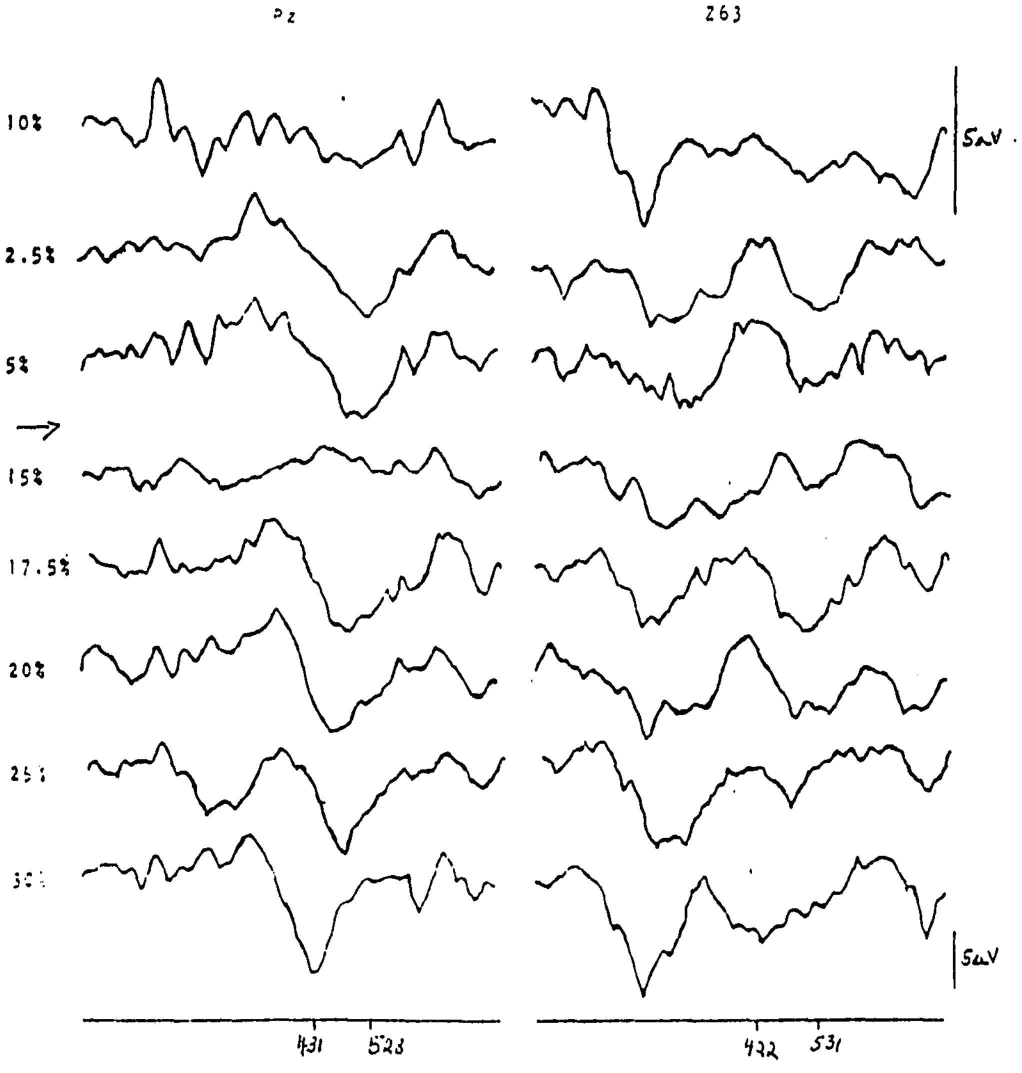

Pz
10%
15%
20%
22.5
25%
401
543
407
525


Pz
203
40%
10%
20%
25%
30%
35%
50%
55%
60%
65%
422
479
417
513

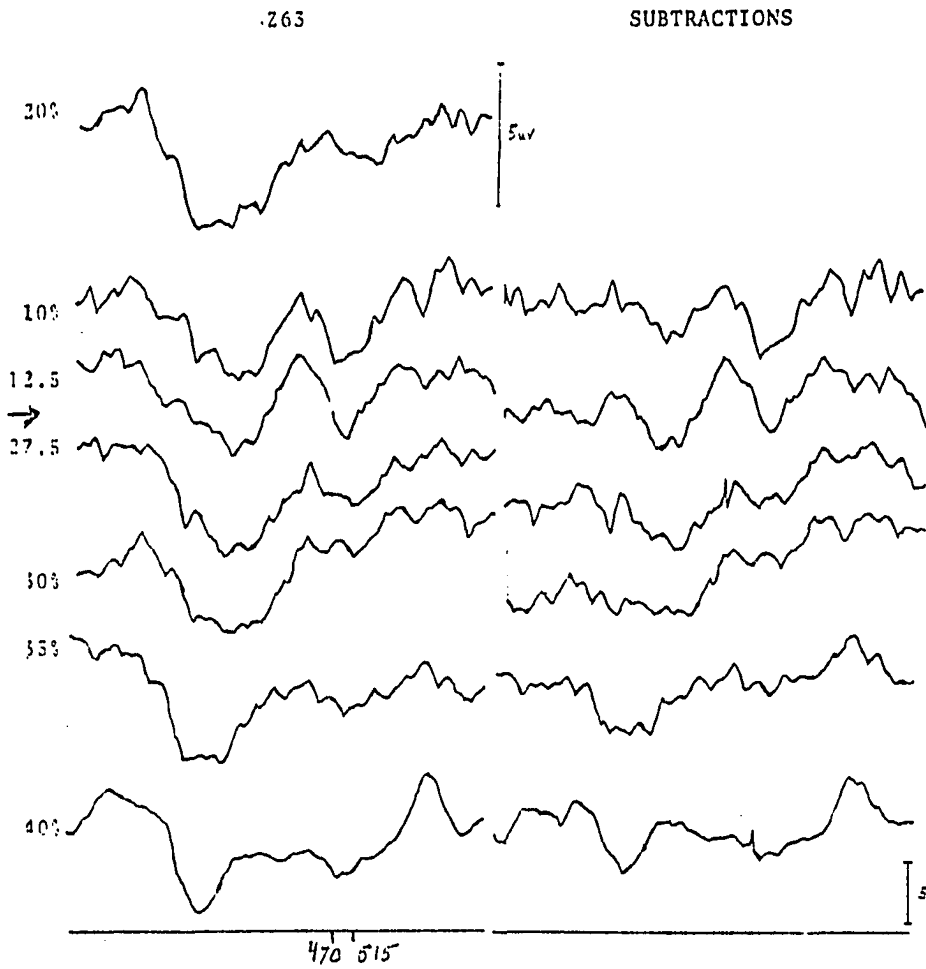

Pz
Z63
50%
10%
15%
20%
25%
30%
35%
40%
65%
5μV
396
512

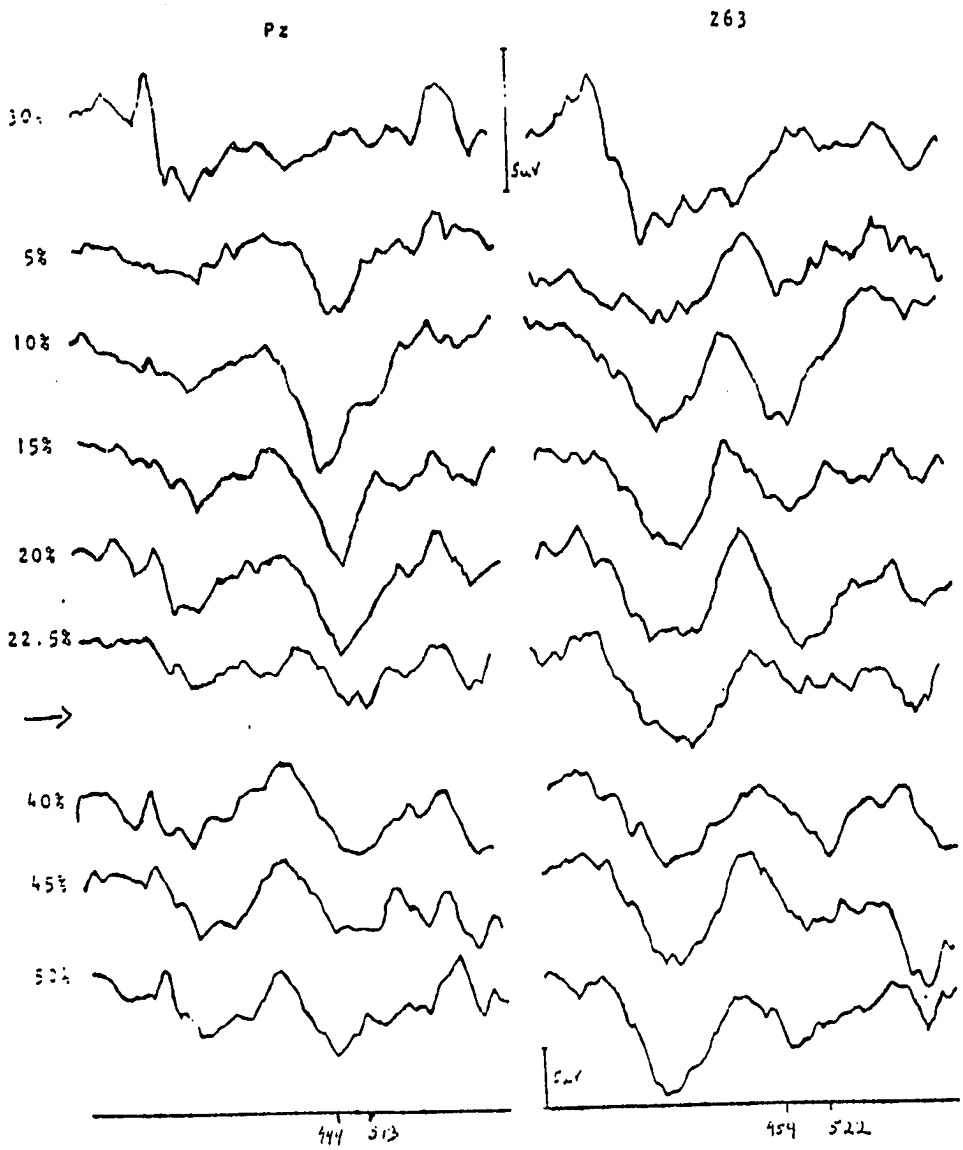


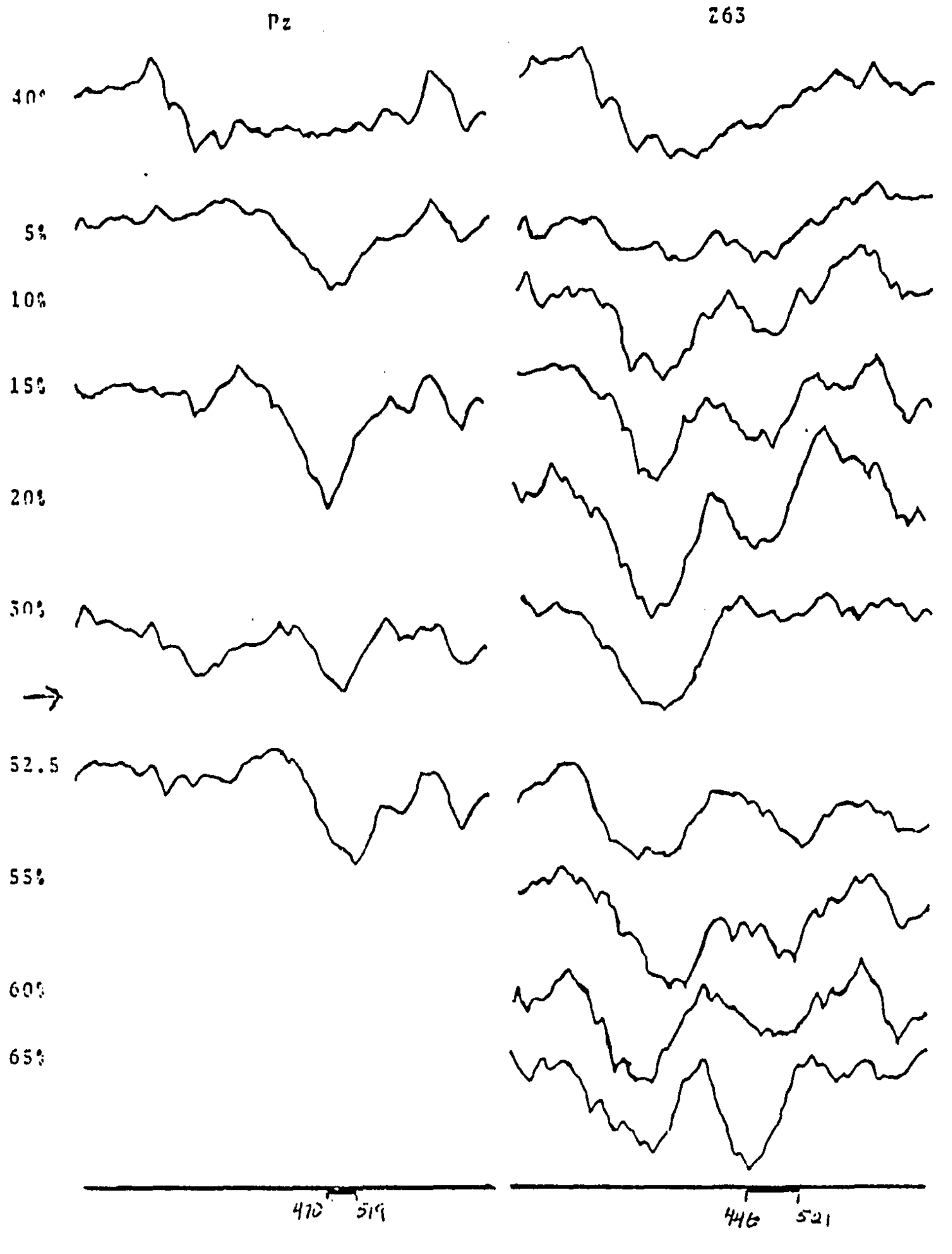
Pz.
Z63
5%
10%
12.5
15%
20%
5uV
5uV
513

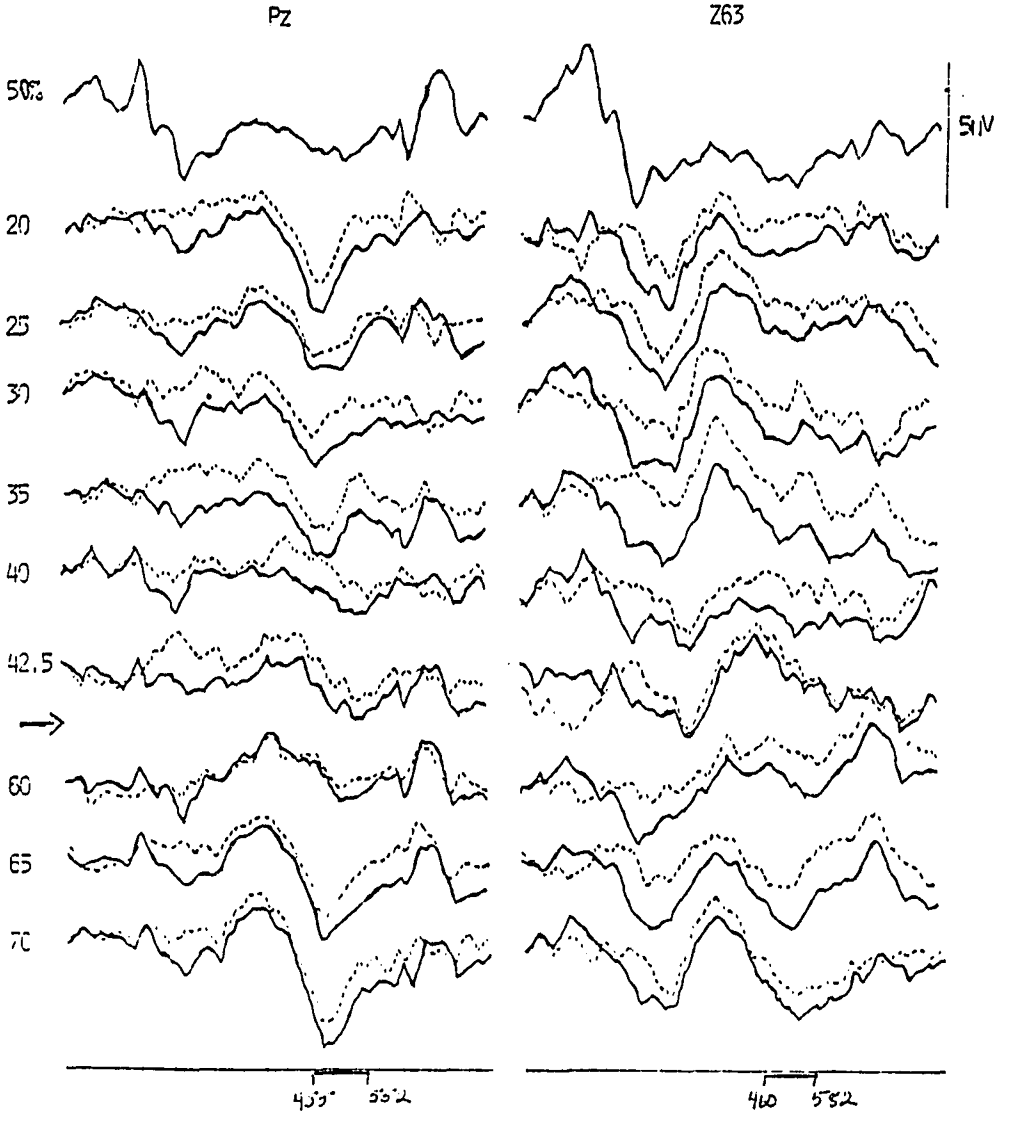


Pz
263
10%
2.5%
5%
15%
17.5%
20%
5uV
5uV
431
528
432
531


.263
SUBTRACTIONS
20%
5uV
10%
12.5
27.5
30%
35%
40%
5uV
470
515


Pz
263
5%
10%
15%
20%
22.5%
40%
45%
5uV
444
513
454
522


Pz
Z63
40%
5%
10%
15%
20%
30%
52.5
55%
60%
65%
410
519
446
521


Pz
Z63
50%
20
25
30
35
40
42.5
60
65
70
5μV
450 552
460 552

APPENDIX C

Pages 226 - 231

I. Tables and figures of the latency of the P3 (top) and the N2-P3 amplitude (bottom), when the difference between the frequent and the rare stimuli was 5% contrast, plotted as a function of the frequent contrasts.

A relationship between latency and amplitude is apparent in that shorter latencies occur with higher amplitudes. Notice there is a tendency for the latency to increase with increasing frequent contrast. These responses are from the three observers.

Pages 232 - 234

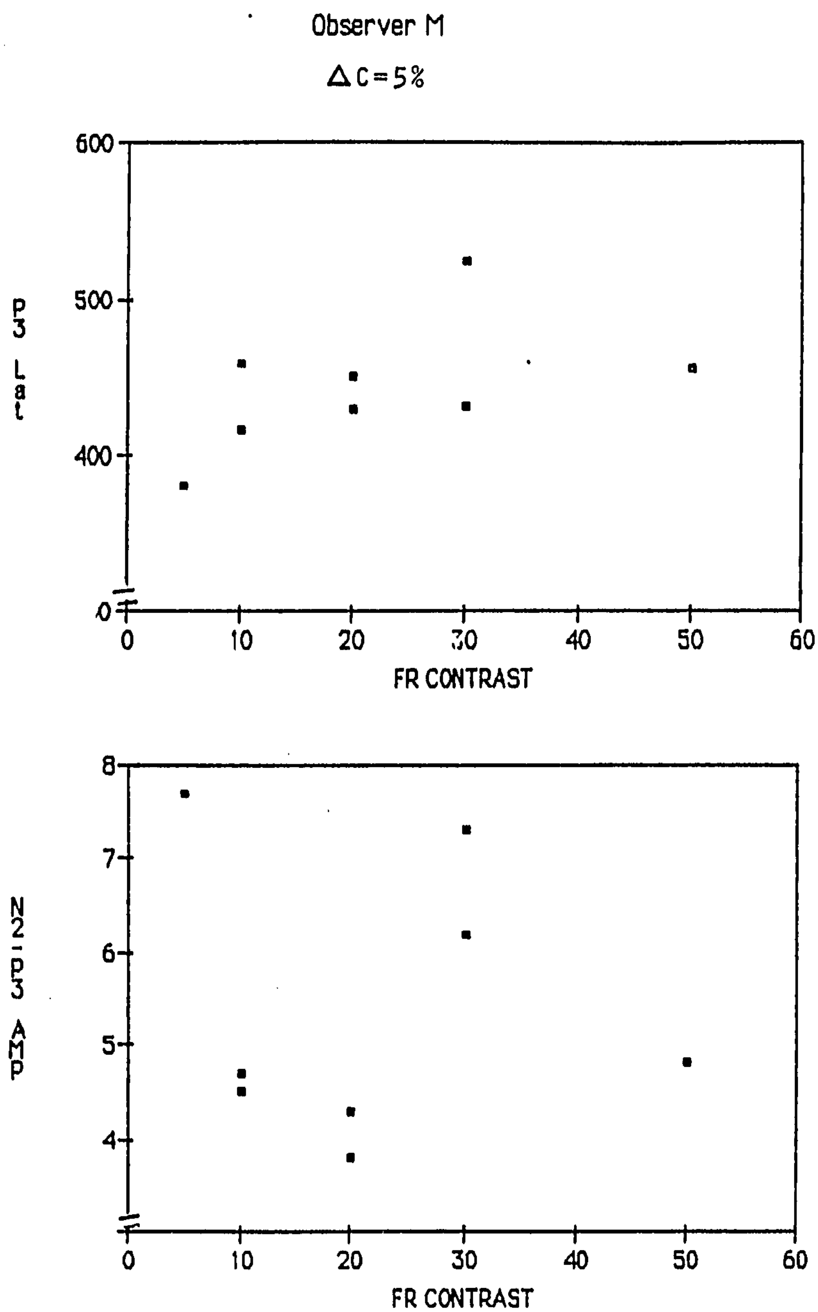
II. Figures that show the latency of the P3 when the $\Delta C/C = .5$ and .25 plotted as a function of the frequent contrasts.

Notice that the function is not flat, therefore equal $\Delta C/C$ does not yield equal P3 latency. Each of the three observers are represented.

Observer M, Represented in the following figure are the P3 latency and amplitude when ΔC = 5% contrast for each of the frequent contrasts.

The data points are:

Frequent Contrast	Rare	ΔC/C	P3 latency	Amplitude
5%	10%	1.	380 ms	7.7µV
10%	5%	.5	459 ms	4.5µV
	15%		416 ms	4.7µV
20%	15%	.25	450 ms	3.8µV
	25%		429 ms	4.3µV
30%	25%	.1667	524 ms	6.2µV
	35%		431 ms	7.3µV
40%	35%	.125	abs	
	45%		abs	
50%	45%	.1	456 ms	4.8µV
	55%		abs	


Observer M
ΔC=5%
600
500
400
0
P3 Lat
0
10
20
30
40
50
60
FR CONTRAST
8
7
6
5
4
N2-P3 AMP
0
10
20
30
40
50
60
FR CONTRAST

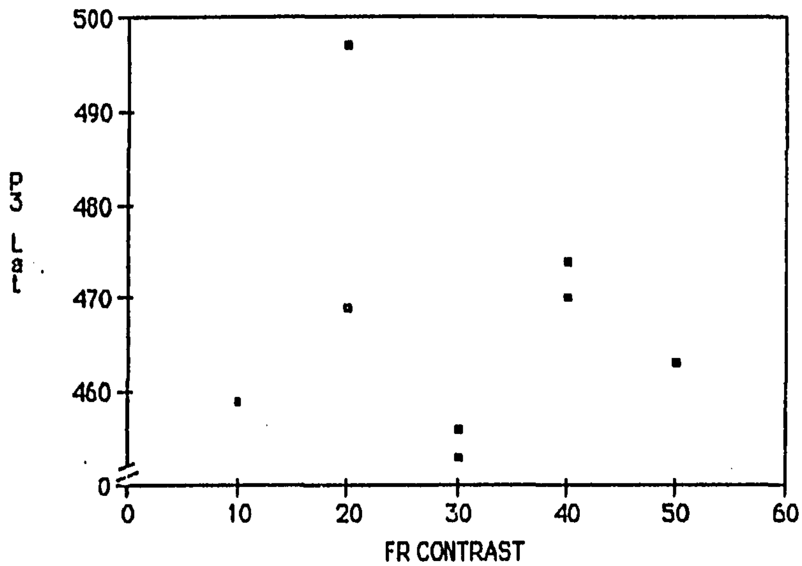
Observer G. Represented in the following figure are the P3 latency and amplitude when ΔC = 10% contrast for each of the frequent contrasts.

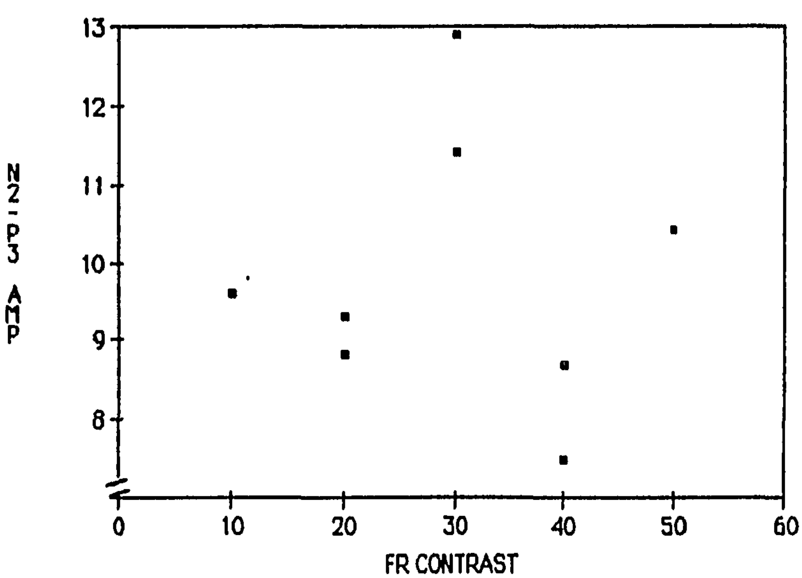
The data points are:

Frequent Contrast	Rare	$\Delta C/C$	P3 latency	Amplitude
5%	15%	2.	not tested	
10%	20%	1.	459 ms	9.6µV
20%	10%	.5	469 ms	8.8µV
	30%		497 ms	9.3µV
30%	20%	.33	456 ms	12.9µV
	40%		453 ms	11.4µV
40%	30%	.25	474 ms	7.5µV
	50%		470 ms	8.7µV
50%	40%	.2	463 ms	10.4µV
	60%		abs	

Observer G

ΔC = 10%





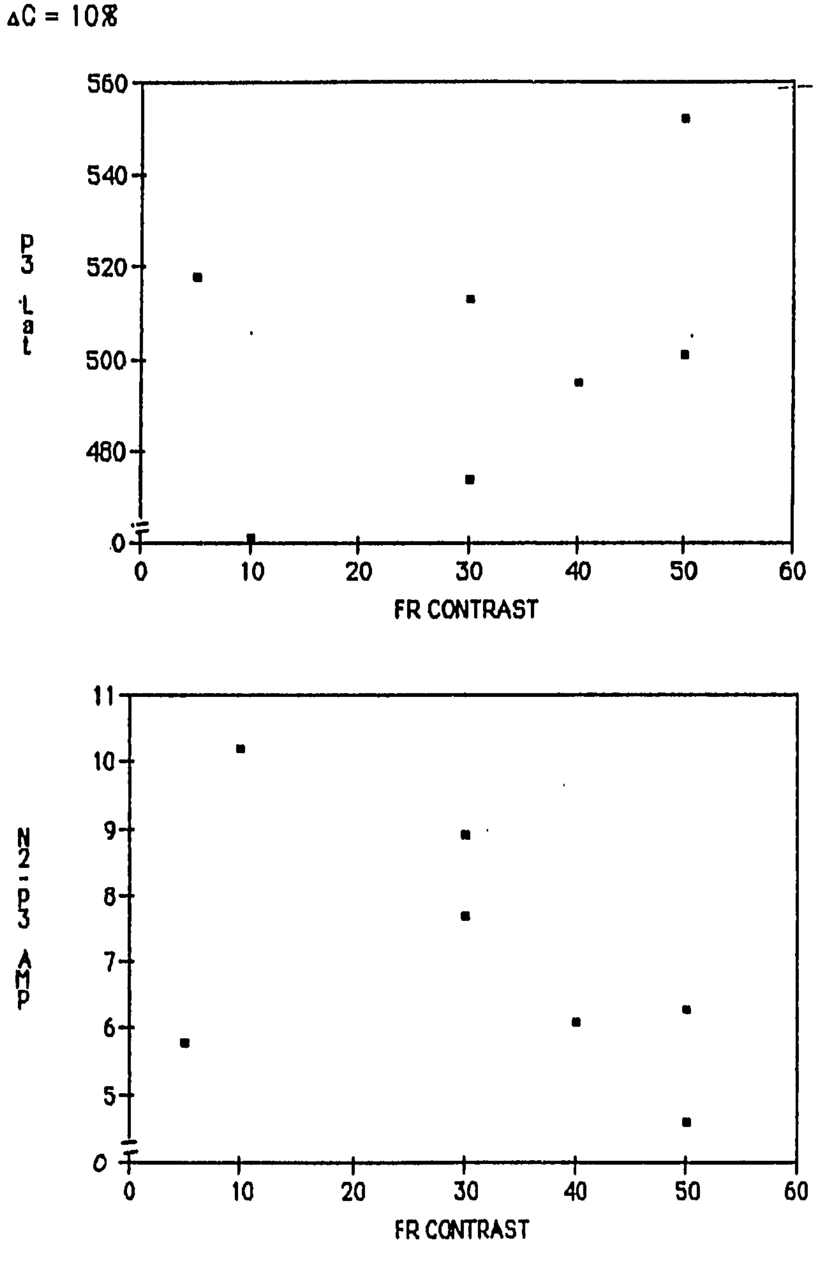
Observer L Represented in the following figure are the P3 latency and amplitude when ΔC = 10% contrast for each of the frequent contrasts.

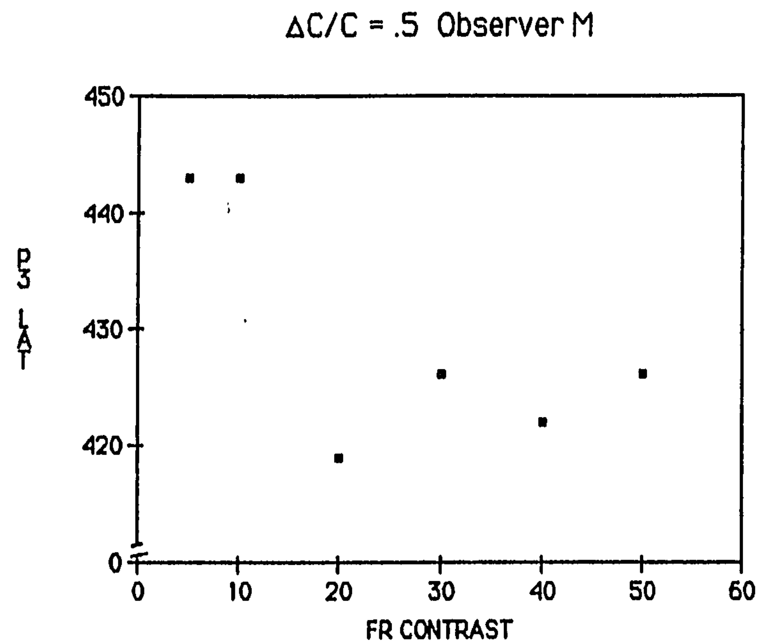
The data points are:

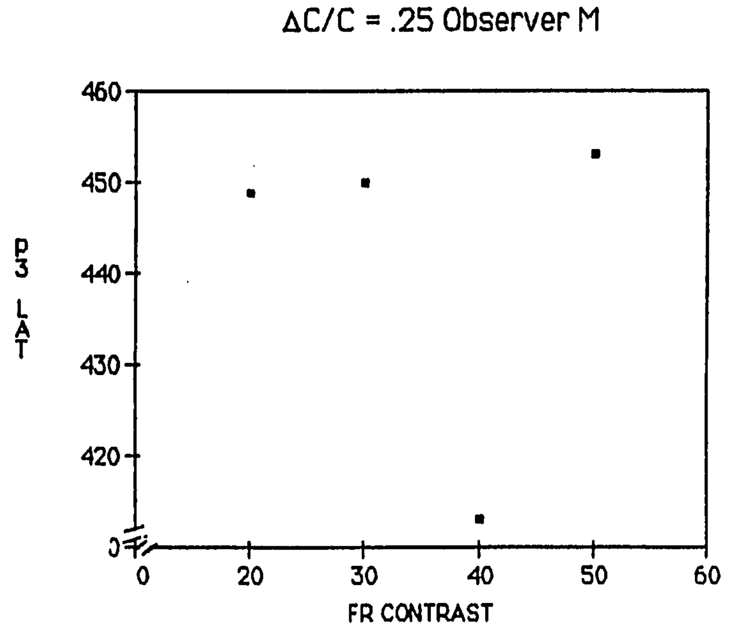
Frequent Contrast	Rare	ΔC/C	P3 latency	Amplitude
5%	15%	2	518 ms	5.8µV
10%	20%	1	461 ms	10.2µV
20%*				
30%	20%	.33	474 ms	8.9µV
	40%		513 ms	7.7µV
40%	30%	.25	495 ms	6.1µV
	50%		abs	
50%	40%	.2	552 ms	4.6µV
	60%		501 ms	6.3µV

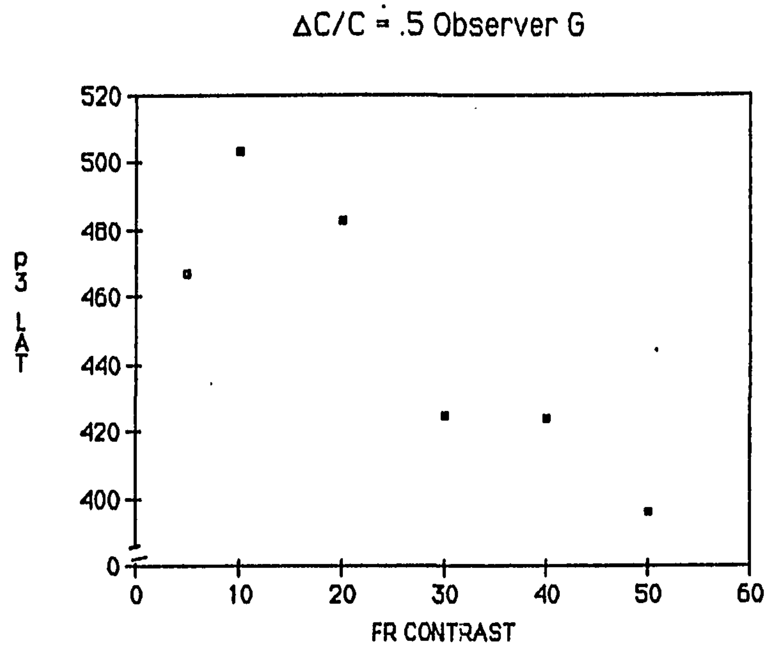
* This observer was not tested with the same electrode when the frequent contrast was 20%.

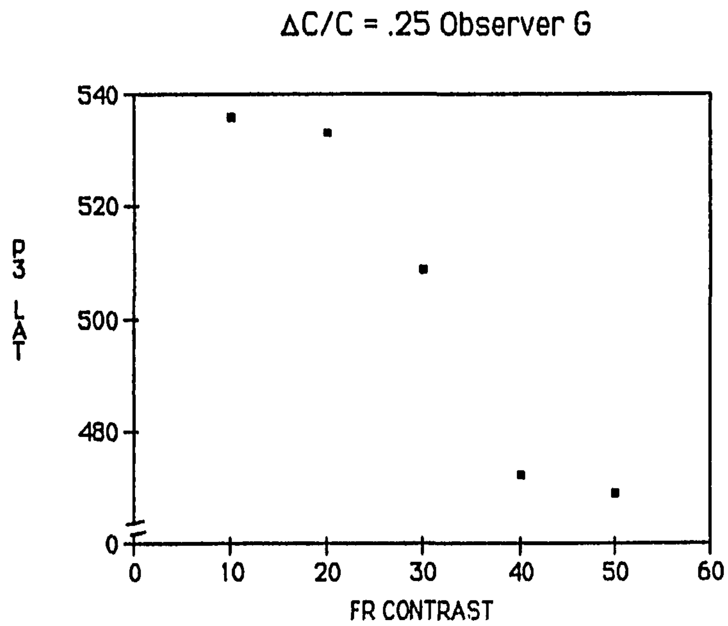
Observer L

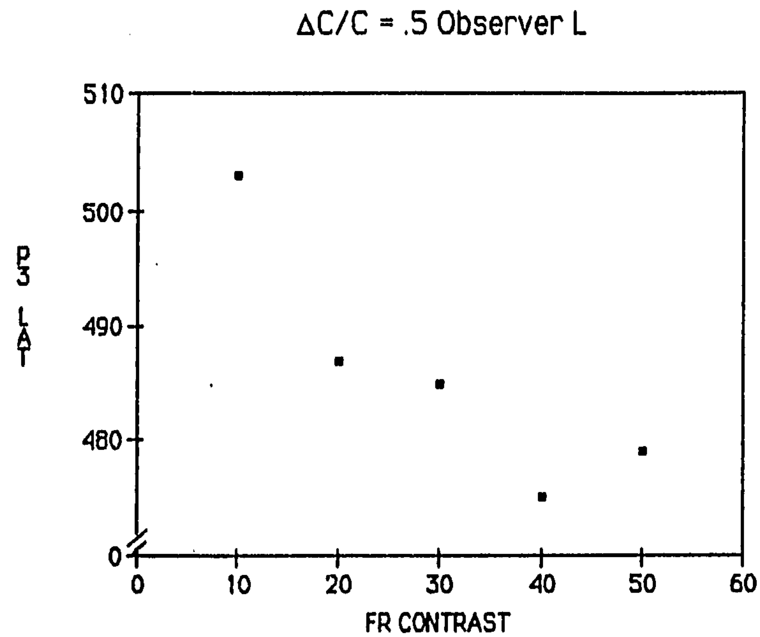

ΔC = 10%
P3 Lat
560
540
520
500
480
0
0
10
20
30
40
50
60
FR CONTRAST
N2-P3 AMP
11
10
9
8
7
6
5
0
0
10
20
30
40
50
60
FR CONTRAST

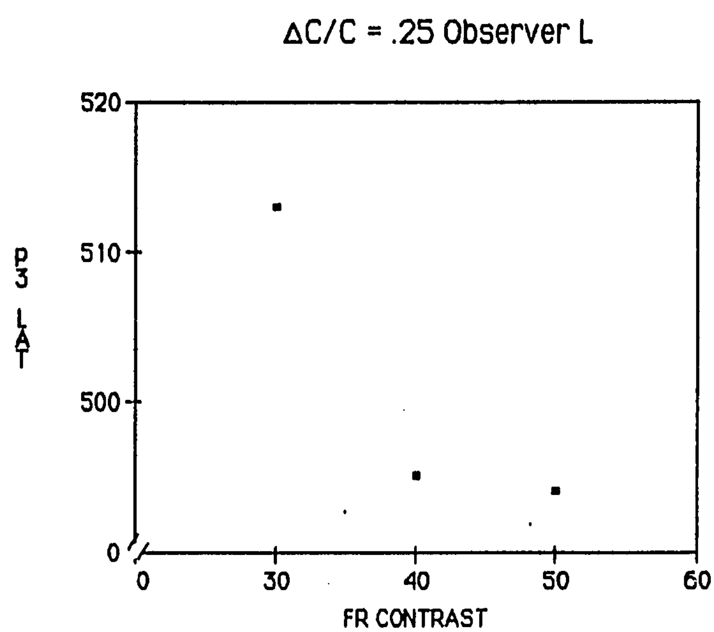

ΔC/C = .5 Observer M
450
440
430
420
0
P3 LAT
0
10
20
30
40
50
60
FR CONTRAST


ΔC/C = .25 Observer M
460
450
440
430
420
0
P3 LAT
0
20
30
40
50
60
FR CONTRAST


ΔC/C = .5 Observer G
520
500
480
460
440
420
400
0
P3 LAT
0
10
20
30
40
50
60
FR CONTRAST


ΔC/C = .25 Observer G
540
520
500
480
0
P3 LAT
0
10
20
30
40
50
60
FR CONTRAST


ΔC/C = .5 Observer L
510
500
490
480
0
P3 LAT
0
10
20
30
40
50
60
FR CONTRAST

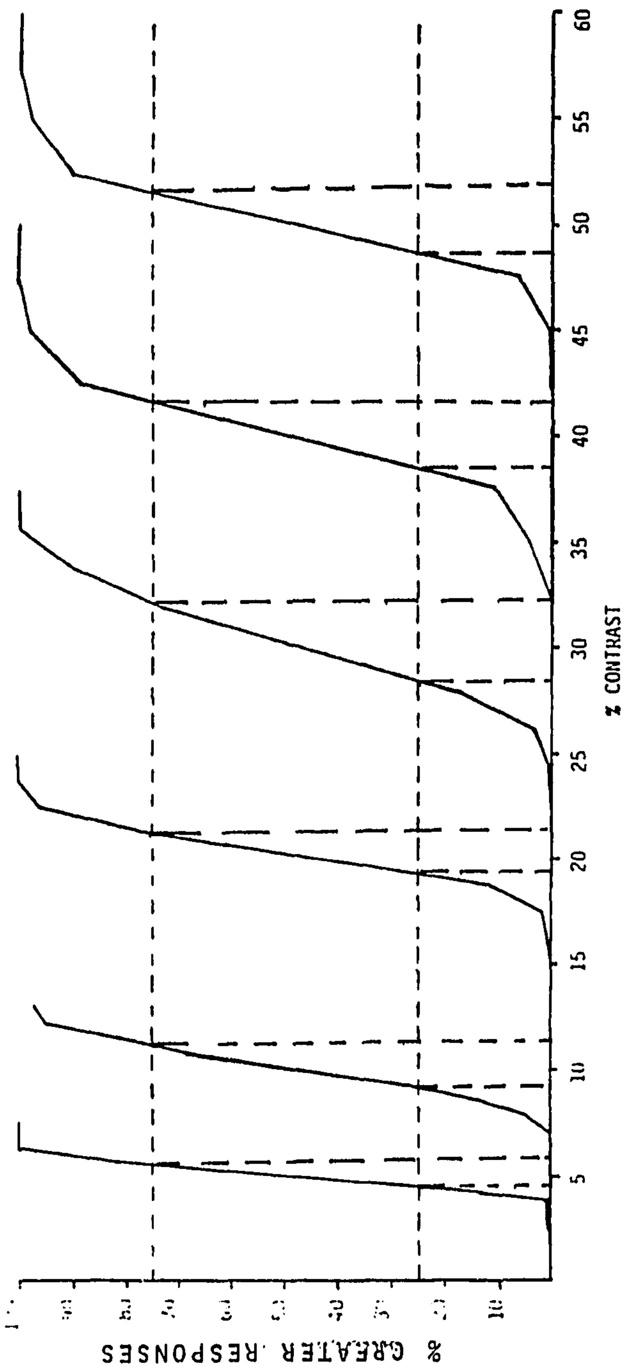

ΔC/C = .25 Observer L
520
510
500
0
P3 LAT
0
30
40
50
60
FR CONTRAST

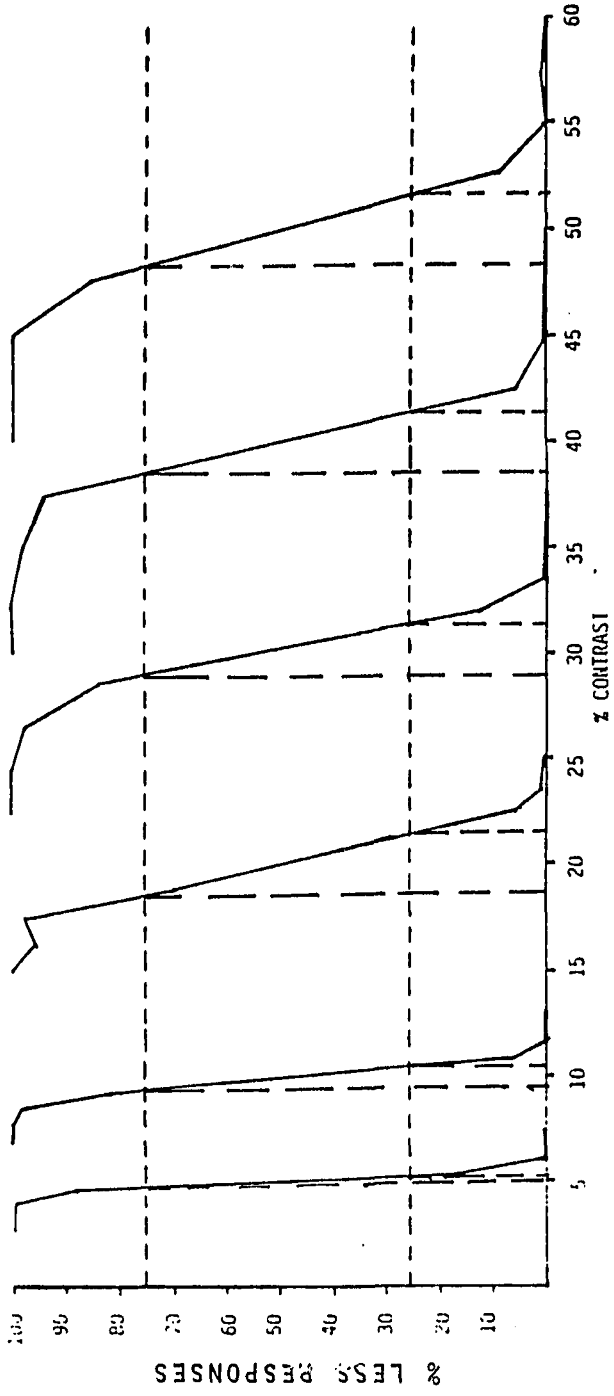
APPENDIX D

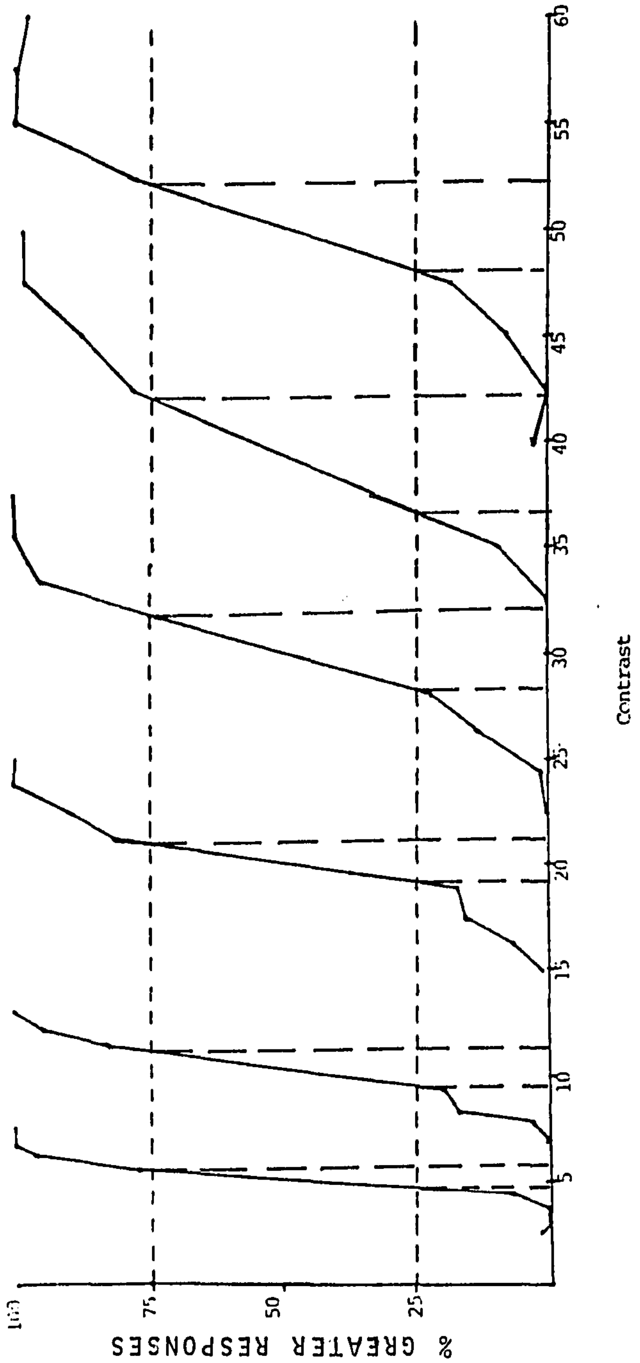
Psychometric functions generated by the three observers.

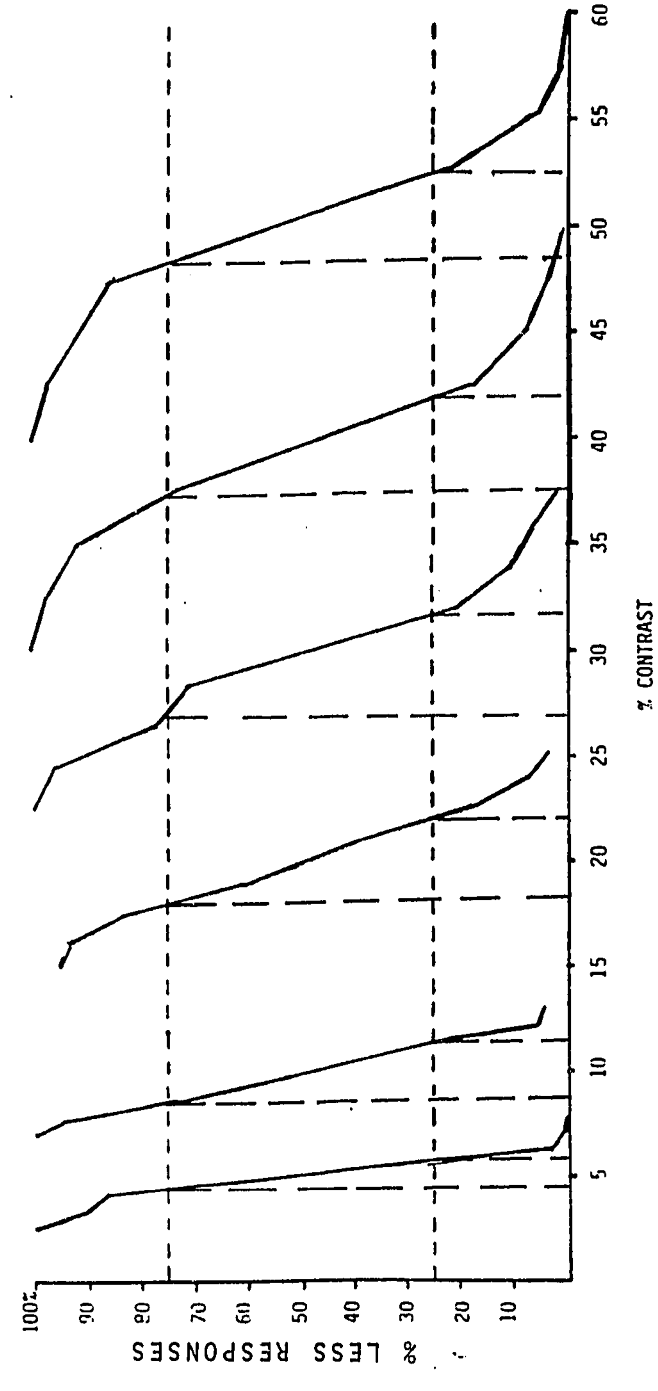
LIST OF FIGURES

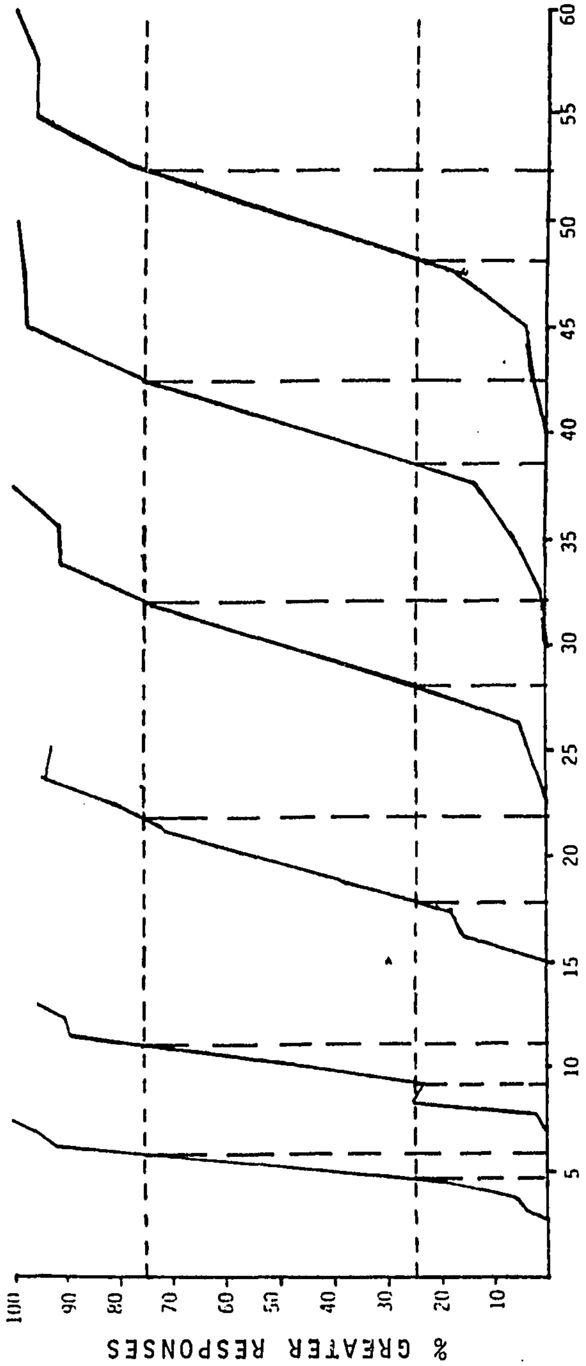
The data for each function was obtained in one session, and consisted of 500 two-interval trials. The horizontal dashed lines indicate where the difference limens were obtained. The vertical dashed lines indicate the amount of contrast within the area of uncertainty around each standard contrast.

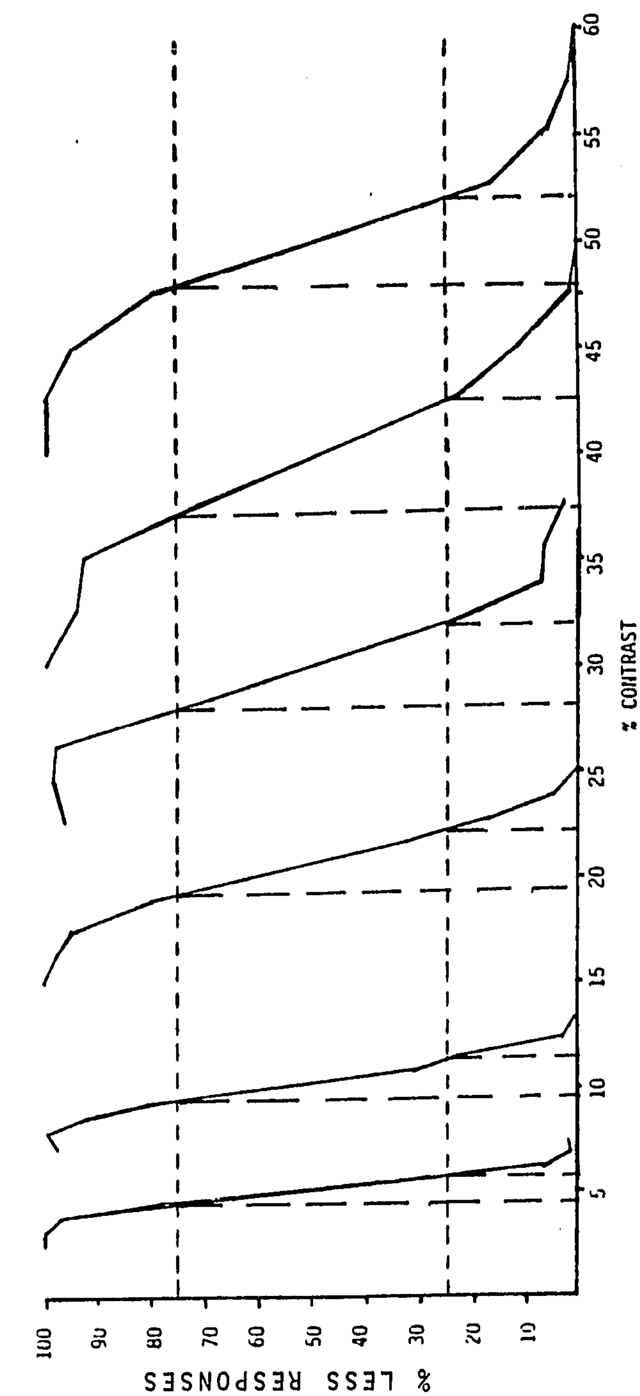

% CONTRAST
5
10
15
20
25
30
35
40
45
50
55
60
% GREATER RESPONSES


% CONTRAST
5
10
15
20
25
30
35
40
45
50
55
60
% LESS RESPONSES
60
50
30
10


% GREATER RESPONSES
100
75
50
25
5
10
15
20
25
30
35
40
45
50
55
60
Contrast


% CONTRAST
% LESS RESPONSES


% GREATER RESPONSES
% CONTRAST
100 90 80 70 60 50 40 30 20 10
5 10 15 20 25 30 35 40 45 50 55 60


% CONTRAST
5
10
15
20
25
30
35
40
45
50
55
60
% LESS RESPONSES
100
90
80
70
60
50
40
30
20
10

GLOSSARY

Amplitude - the difference in microvolts between a positive and a negative peak or between baseline and a designated peak.

Component - identified by polarity (positive or negative), latency (in msec after stimulus onset) and amplitude.

Condition - in the electrophysiological study; it is the recording of one frequent contrast and one rare contrast presented for a total of 512 stimulus presentations. This term is not used in the psychophysical study.

Contrast - The difference between the maximum luminance of the grating pattern and the minimum luminance of the pattern divided by their sum: (Lmax-Lmin)/(Lmax+Lmin).

ΔC/C - in the electrophysiological study, the difference between the frequent and the rare contrasts divided by the frequent contrast; in the psychophysical study, the minimum difference between two contrasts that was responded to as different divided by the standard stimulus.

Difference threshold (DL) - The minimum difference between two stimuli that can be responded to as being different 75% of the time. In the electrophysiological study, defined as the minimum contrast that evoked a P3.

ERP-JND - The minimum **ΔC/C** between two grating patterns that elicited a waveform with an evident P3.

Event-Related potentials (ERPs) - Electrical activity, recorded from the scalp, which is either the response to an external event or related to an internal event.

Frequent Stimulus - referred to in the electrophysiological study as the contrast against which the rare stimuli are compared, presented 90% of the time.

Latency - is one of the descriptions of the ERP, latency is referred to as the time, in msec, after the onset of the stimulus that a peak in the waveform is observed.

N2 - a peak in the waveform with a negative polarity that occurred in the 200-350 msec latency range.

Oddball paradigm - a randomized (Bernoulli) series of two classes of stimulus events presented to an observer who must discriminate them, and make some kind of differential reaction.

P300 (P3) - a peak in the waveform with a positive polarity that occurred in the 350-550 msec latency range.

Pz - scalp location which is on the midline, 30% of the distance between the inion and the nasion.

Rare stimulus - the stimulus that was presented 10% of the time in the electrophysiological study in order to evoke a P3 in the waveform.

Session - in the electrophysiological study, a session lasted from two to four hours in which one frequent contrast was compared with several rare contrasts; in the psychophysiological study, a session lasted about an hour in which one standard contrast was compared with eight other contrasts, and the observer had to indicate whether the comparison stimuli had either a higher or a lower contrast.

Standard contrast - also referred to as the **Standard stimulus** in the psychophysical study. In the electrophysiological study, also referred to as the **frequent stimulus**.

Trial - in the psychophysical study, one of 500 trials that composed a session, each trial consisted of two intervals in which a standard stimulus and a comparison stimulus were presented.

Visual evoked potentials (VEP) - Electrical activity, recorded from the scalp, which is considered the response to visual stimulation, and is largely independent of the state of the observer.

Z63 - scalp location which is on the midline, which is 63% of the distance between the inion and the nasion.

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