

INFORMATION TO USERS

This reproduction was made from a copy of a manuscript sent to us for publication and microfilming. While the most advanced technology has been used to photograph and reproduce this manuscript, the quality of the reproduction is heavily dependent upon the quality of the material submitted. Pages in any manuscript may have indistinct print. In all cases the best available copy has been filmed.

The following explanation of techniques is provided to help clarify notations which may appear on this reproduction.

1. Manuscripts may not always be complete. When it is not possible to obtain missing pages, a note appears to indicate this.
2. When copyrighted materials are removed from the manuscript, a note appears to indicate this.
3. Oversize materials (maps, drawings, and charts) are photographed by sectioning the original, beginning at the upper left hand corner and continuing from left to right in equal sections with small overlaps. Each oversize page is also filmed as one exposure and is available, for an additional charge, as a standard 35mm slide or in black and white paper format.*
4. Most photographs reproduce acceptably on positive microfilm or microfiche but lack clarity on xerographic copies made from the microfilm. For an additional charge, all photographs are available in black and white standard 35mm slide format.*

*For more information about black and white slides or enlarged paper reproductions, please contact the Dissertations Customer Services Department.

U·M·I Dissertation
Information Service

University Microfilms International
A Bell & Howell Information Company
300 N. Zeeb Road, Ann Arbor, Michigan 48106

8629672

Berman, Steven Mark

EVENT RELATED POTENTIAL SIGNS OF SELECTIVE ATTENTION: THE
EFFECT OF CHANNEL PROBABILITY ON PROCESSING NEGATIVITY

City University of New York

PH.D. 1986

University
Microfilms
International 300 N. Zeeb Road, Ann Arbor, MI 48106

**EVENT RELATED POTENTIAL SIGNS OF SELECTIVE ATTENTION:
THE EFFECT OF CHANNEL PROBABILITY ON PROCESSING NEGATIVITY**

by

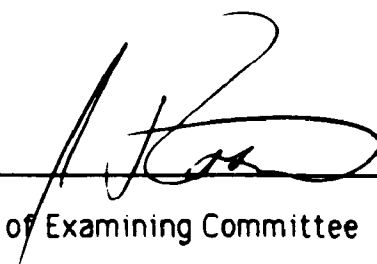
STEVEN MARK BERMAN

**A dissertation submitted to the graduate faculty in Psychology
in partial fulfillment of the requirements for the degree of
Doctor of Philosophy, the City University of New York.**

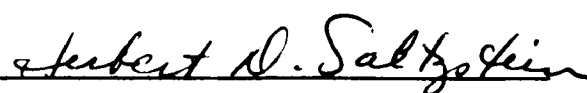
1986

This manuscript has been read and accepted for the Graduate Faculty in Psychology in satisfaction of the dissertation requirement for the Doctor of Philosophy.

9/26/86
Date


Chair of Examining Committee

September 29 1986
Date


Executive Officer

Jeffrey Rosen, Ph.D.

Walter Ritter, Ph.D.

Louis Gerstman, Ph.D.

John Antrobus, Ph.D.

David Friedman, Ph.D.

Supervisory Committee

The City University of New York

TABLE OF CONTENTS

Figure and table index	iv
Introduction	1
Event-related potentials	3
ERPs and attention: Processing negativity	7
Probability and attention	15
Method	21
Subjects	21
Stimuli	21
Recording System	22
Procedure	23
Eye-movement control	25
Results	26
Standard tones	26
Long tones	29
Read control condition	30
Ocular control	31
Discussion	33
Appendix A (A Framework for ERP Attention Effects)	49
Perception	50
Attention	53
Endogenous ERP components: Contingent Negative Variation	67
Endogenous ERP components: Late Positive Component	70
A model of selective attention	79
Appendix B (Figures 1-16 and Table 1)	91
Appendix C (Additional Subject Information)	109
Appendix D (Subject ERPs for high vs other channel probabilities)	111
References	124

FIGURE AND TABLE INDEX
(Appendix B: pp 92-108)

- Figure 1. The human auditory event-related potential on a log scale
- Figure 2. Grand mean ERPs for standard tones when attended and unattended in all channel probability conditions
- Figure 3. Effect of channel probability on processing negativity
- Figure 4. Peak attention-related negativity prior to 320 msec as a function of channel probability
- Figure 5. Grand mean ERPs for standard tones with high channel probabilities (70-90%) and other probabilities (10-60%)
- Figure 6. Timecourse of the effect of high channel probability on processing negativity (Nd)
- Figure 7. ERPs to .5 and 1 KHz standard tones in attended and unattended channels having channel probabilities 50, 60 and 70%
- Figure 8. Individual grand mean Nds for channel probabilities 10-60% and 70-90%
- Figure 9. Grand mean ERPs for deviant long tones when attended and unattended in all channel probability conditions
- Figure 10. Effect of channel probability on attention-related negativity in the ERPs of deviant long tones
- Figure 11. High deviant tone Cz ERPs where channel probabilities were equal for six randomly selected subjects show strong Nd, but high variability over the rest of the timebase.
- Figure 12. Grand mean ERPs for visual distractor condition standard tones
- Figure 13. Grand mean ERPs for visual distractor condition deviant long tones
- Figure 14. Grand mean event-related potentials for visual distractor control standard tones with 70% channel probability minus those with 30% channel probability demonstrates pitch-specific refractoriness

Figure 15. ERPs for standard tones in ocular control EN

Figure 16. Temporal relationships of human event-related potentials in a cued oddball paradigm where a target followed the cue

Table 1. Nd measured as negative area from 80-480 msec for channel probabilities 10-60 and 70-90%

In recent years, attempts to understand human cognition have been aided by the use of averaged evoked electrical responses to sensory stimuli (Ritter et al. 1983, Sanquist et al. 1980, Pritchard 1981, Hansen & Hillyard 1980, Grossberg 1980, Duncan-Johnson & Donchin 1982, Posner 1983). Because of the precise time-locking of this event related potential (ERP), it is particularly suited to testing theoretical formulations of information processing. For example; do the postulated stages process serially, one after the other like a computer? Or can stages proceed in parallel, as if many microprocessors were operating separately, while building up data in a central bank? At what point does perception become influenced by set? How much information processing is controlled by a central executive, and how much proceeds by relatively rigid but effortless automatic processing (Shiffrin & Schneider 1977)?

Use of ERP technology has contributed to the resurgence in recent decades of a psychological construct that had fallen into disfavor earlier in this century: the idea of attention. The word has become firmly entrenched in the popular lexicon, where it is associated with selection of a subset of stimuli by a voluntary or imposed mental act. Most experimental psychologists have sidestepped formal conceptual definition and made do with some operational measure. Some have operationalized attention through measures of differential response presumed to derive from selective processing. Others have used set or degree of effort defined by instructional parameters. These approaches recall William James division into active attention and passive attention (James 1890). Active attention is a conscious strategy for selection, while passive attention involves the innate "grabbing" of more attention by some sensory events. Clearly, some

of the influences on the differential processing underlying differential response are not under conscious control.

This dissertation describes an experiment testing the effect of a probability manipulation on the ERP component most closely identified with selective attention. This section will present a brief tutorial of ERP methodology, a review of the ERP component under investigation, and some relevant behavioral and ERP findings on the type of manipulation employed by the experiment. After presentation of the experiment, the discussion section will expand these issues in interpretation of the experimental results. Appendix A will present a more widespread survey of theoretical and empirical issues to serve as a policy statement of my personal point of departure for understanding the intersection of the cognitive and neural sciences. This will culminate in the generation of a framework I will propose for understanding the effects of attention on brain electrical activity.

It is possible to use ERPs to validate theories of attention without reference to a theory of perception, anatomical data, or most of what is known about physiology. With the one phrenological-type assumption that the electrical "bumps" which make up an ERP represent some underlying cognitive process, a discussion could be restricted to fitting behavioral data to theoretical concepts. An approach like this may be useful in that it limits speculation. However, it also loses much explanatory potential. Because I feel that one of the most productive activities of science is integration of separate data bases, this dissertation will consider information from all related areas of inquiry.

Event-Related Potentials

Use of event-related potentials has been greatly enhanced by the ability of computers to average the electroencephalographic (EEG) record that follows groups of individual stimuli. Generally, a non-invasive scalp electrode records potential deflections and shifts relative to a reference electrode placed in a hopefully neutral location. A computer can average across trials the potential difference between these two electrodes at regular intervals over a set time period. For example; the analog record of the EEG can be converted to a digital value every 2 msec for a period of 1 second beginning when a tone sounds. These 500 numbers are stored in an internal array. When the tone sounds a second time, a second set of 500 numbers can be averaged on-line with the first set. So if the first number showed the active electrode to be 6 μ volts more positive than the reference electrode when the first tone sounded, but only 2 μ volts electropositive the second time, the average deposited in the array would be 4 μ volts. In this way, thousands of a brain's responses to identical events can be averaged. Any brain electrical activity not related to the common event will average out to zero, leaving only an electrical record of activity that is specifically event-related.

When an auditory signal is the eliciting event, figure 1 summarizes the sequence of ERPs that can be recorded (see figure 1, Appendix B). Although a log scale can show all of these phenomena, individual experiments must choose a specific section of this timescale to study, in order to attain proper resolution with a limited number of data points. The earliest reliable responses should be generated at the periphery. (In figure 1 the positive bump recorded at about 2 msec has been shown to be generated by the auditory nerve.) The following 4 positive deflections

represent synchronous firing in successive brainstem pathways, with the fifth bump receiving major contributions from midbrain (Stockard et al. 1977, Hashimoto et al. 1981). The averaging out of all non-contingent potentials has reduced the amplitude of recorded brain electrical activity from tens of μ volts to tenths of μ volts. Yet this record of five bumps, known collectively as the brainstem auditory evoked response (BAER), is quite reliable both within and between subjects (Jewett & Williston 1971, Picton et al. 1974, Picton & Hillyard 1974).

The potentials from about 10 to 50 msec are collectively known as the auditory middle latency responses, and those after 50 msec as the long latency potentials or late waves (Polich & Starr 1983). As the dotted line in Figure 1 shows, it is primarily with this timeframe that we will be concerned in studying the effects of attention. Because some late ERP components depend on internal set, they have been labeled endogenous components (Rockstroh et al. 1982-Chapter 1), in comparison to the exogenous components, which are relatively stimulus-determined. In other words, the early exogenous ERP components are evoked by a stimulus regardless of how it is being processed, while the endogenous components vary greatly depending on the manner in which the signal is processed. Care must be taken to distinguish between the deflections recorded and the underlying components hypothesized to produce them. If we process information in parallel (Kahneman 1973-chapter 8, Anderson 1983-chapter 3), different generators related to different processors may overlap temporally. Because both positive and negative potentials reduce with summation, mathematical techniques and experimental consensus are needed to derive reliable models of the cerebral activity that produces the ERP record.

Sutton and Ruchkin (1984) have proposed 7 criteria for establishing component identity. They include latency, polarity, sequence (relation to other components), scalp topography, relation to physical characteristics of stimuli (such as modality), functional role (although this has usually been quite difficult to establish), and relationship with subpopulation or state variables. Although no single criterion can establish a component, by manipulating such variables as the location of recording electrodes, the characteristics of the eliciting events, and the instructions given to subjects, we build up converging evidence that is used to define components.

Mathematical techniques for component isolation have included subtraction waveforms and principal components analysis (PCA), (Donchin & Heffley 1979). A subtraction waveform attempts to graph the effect of a particular variable. For instance, if one wished to show the effect of increasing the amplitude of a click from 40 to 60 db, one could subtract the ERP evoked by the 40 db click from that evoked by the louder one. The electrical activity produced in response to the softer event would vanish, leaving only the ERP effects of the experimental manipulation. (This assumes the component of interest is not influenced by latency changes.)

PCA is a factor analytic method of looking for covariance in groups of serial measures (like ERP data points) in order to break grand mean ERP waveforms into independent orthogonal components. The components which represent the largest portions of the between waveform variance are generally rotated to resemble previously identified ERP components such as P3 and N1. The effect of experimental manipulations on the rotated PCA components can then be analyzed by analyses of variance (ANOVAs) or other inferential statistics.

These techniques must be used with caution. When attempting to isolate the effects of attention to a stimulus, the unattended ERP is often subtracted from the attended response to an identical stimulus. Besides being confounded with longitudinal effects and obscured by latency shifts, the resulting difference waveform does not distinguish between greater positivity of one waveform and greater negativity of the other.

It has been pointed out that a PCA may overvalue the usefulness of separating ERPs into independent orthogonal components (Norman 1984). Since the brain is presumably an integrated system, it may be counter-productive to let our statistics guide our interpretation. More importantly, there is no real need for PCA except where two components overlap in time, and the validity of the technique has recently been questioned in just that situation (Wood & McCarthy 1984). While the proponents of PCA have used hypothetical models to demonstrate extraction of overlapping components, Wood and McCarthy found that a PCA failed to properly retrieve specified components in a computer model of an ERP, if components overlapped. Although only 8-10% of the variance was misallocated by the rotated PCA, this resulted in type I error rates as high as 81% when analyses of variance were performed on the factor scores!

Mathematical transformations can provide useful sources of converging evidence. However, at this stage in the development of ERP analysis it is still best to remain firmly rooted in the recorded waveforms from which any subsequent transformations must derive. For this reason, original waveforms should always be presented along with any transformed data.

ERPs and Attention : Processing Negativity

The ERP most strongly related to selective attention is the processing negativity, also known as the negative deflection (Nd). Processing negativity refers to occurrence of a negative potential after the event attended to (Näätänen 1982). Although some authors have reported earlier attention effects (Lukas 1981, McCallum & Curry 1984), the first widely agreed upon negativity begins 50-100 msec poststimulus. Early reports of this effect measured it as an increase in the amplitude of the exogenous negative wave (N1) found around 100 msec after auditory stimuli (see figure 1, Appendix B). It was measured in a two-channel paradigm (such as sequences of tones that could appear in either ear) where only a distinguishable group of sounds in one "attended" channel was responded to by motor task or counting. Using the same stimuli for two runs where only the attended channel differed, larger N1s were demonstrated for attended channels (Hillyard et al. 1973). Most often, ears served as channels and a small randomly determined set of higher pitched tones represented the target stimuli (i.e., for run 1 count the rare high tones in the right ear, but for run 2 count the rare high tones in the left ear). Hillyard interpreted the N1 effect as representing Broadbent's (1970) proposed stimulus-set attentional operation, with a later positive potential to targets (P300) interpreted as reflecting Broadbent's response-set (see page 58).

The situation where a sequence of stimuli features one rare stimulus type designated as a target has come to be referred to as the oddball paradigm. In Nd experiments, there are two, (or occasionally three), easily distinguishable types of stimuli presented in random sequences with about equal probability. These groups (physical locations, pitches, colors, etc.) are taken to define information channels. Within each channel are

infrequent deviant stimuli. These "deviants" represent targets when their channel is attended. The common events in each channel are designated as "standards".

Näätänen (1975) suggested that the N1 effect might be superimposed over, but otherwise unrelated to the exogenous N1. Näätänen, Gaillard and Mäntysalo (1978) strengthened this hypothesis using a paradigm which made the interstimulus interval constant and lengthened it to 800 msec. There was no effect on N1 amplitude, but a later negative displacement (Nd) in the waveform of the attended non-targets, relative to that of unattended non-targets, was interpreted as a separate endogenous potential related to attention. Näätänen and associates (1978) suggested that prior examples of the N1 effect were caused by processing negativity, which was superimposed over N1 only because of parametric values chosen by those studies.

Further studies have clarified some of the characteristics of Nd. Its latency is sensitive to interstimulus interval such that with very short intervals, it may be seen as early as 50 msec but with interstimulus intervals on the order of a second, it may not appear until 150 msec. Long interstimulus intervals also allow separation of Nd into an early centrally-maximized component and a later frontally-maximized component that tends to be larger and sensitive to interstimulus interval. Longer interstimulus intervals increased the amplitude of late Nd tenfold and shifted peak latencies from those indistinguishable with an N1 effect to as late as 350 msec with return to baseline past 700 msec (Näätänen, et al. 1981). Whatever operation it indexes can have variable onsets and offsets.

Nd is operationalized as that negativity derived by subtracting the ERP of unattended standards from the ERP produced by the same stimuli as

attended standards. While it is important to have a quantifiable measure, this procedure may be misleading. As previously mentioned, subtraction waveforms can not distinguish between greater negativity in the one waveform and greater positivity in the other. Moreover, Näätänen (1982) has pointed out that if Nd is defined as the processing that selects a stimulus as a member of an attended set, then even the unattended channel events must evoke some Nd before being rejected. This view explains why channels that are more distant from the attended one show earlier (faster rejection) Nd (Hansen & Hillyard 1980), and clarifies the subtraction waveform as the processing difference between channels, rather than amount of total processing negativity. Although the terms have often been used interchangeably in the literature, this dissertation will use processing negativity to denote the negative component thought to relate to attentive information processing and Nd to refer to the subtraction negativity seen in the (as attended - as unattended) waveform.

A few studies in the somatosensory and visual stimulus modalities have both confirmed Nd presence and suggested that the early component may be largest over cortical sensory and association areas corresponding to the modality of stimulation (Desmedt & Robertson 1977, Harter & Previc 1978).

Hansen and Hillyard (1980) showed that increasing the separation between the channels (by making the two pitches further apart) caused the processing negativity to begin earlier and last longer. Adding an additional dimension that separates channels, as when using ear channels that also have different pitch ranges, also increases the effect (Schwent et.al. 1976). Unfortunately, this study, like many others investigating attention in

dichotic listening paradigms, reports the effect only in terms of N1 amplitude, thereby limiting their contribution.¹

Another study of this type of was reported by Donald and Young (1980) to clarify the development of processing negativity within a session. They broke the usual dichotic listening task into many 10 second blocks (of 16 tones each) separated by 6 second inter-block intervals. In this way, they obtained average waveforms for the first through sixteenth positions by averaging across blocks. The N1 effect (deeper N1 in the attended ear) appeared even at position 1 and held fairly constant, although N1 itself habituated considerably between the first and second positions. However, the effect did not appear during the first 30-45 seconds in each session (the first few blocks). It also vanished after about 7 minutes of attending. Since molar performance (detection of occasional deviants in the attended ear) did not decline with the attention effect, questions of the importance of this phenomenon and of its course of development must be addressed by further research.

A subsequent report proposed that N1 differences were the result of less habituation in the attended channel (Donald & Little 1981). By varying the within-channel probability of targets between 1/4 and 1/16, the N1 effect was shown to be largest at the higher target probabilities. The authors proposed that the greater habituation found with more frequent stimuli accounted for a better N1 effect (derived by attenuating habituation). Because only N1 amplitude was measured, the results in terms

¹Dichotic listening tasks generally play sounds in both ears. Subjects are instructed to get specified information from a given ear and ignore the sounds in the other one (focused attention), or to get information from both ears (divided attention). In ERP experiments, each sound appears in one ear only, without a concurrent sound in the other ear.

of the total processing negativity are not clear. Use of an inappropriate high pass setting further limits the significance of the studies of Donald and associates.

The importance of this study for the present experiment lies in the finding of amplitude changes in what today would be attributed to Nd with a probability manipulation. Nd is generally considered to be insensitive to the manipulation of probability (Gaillard 1985, Ritter et al. 1984), despite major effects on P300 (see LPC section of Appendix A). However, examination of the evidence for this view indicates that it rests on the observation that Nd for low probability deviants is about equal to Nd for high probability standards.

In general, the type of task performed does not appear to strongly affect Nd. Tasks have been either to count or respond motorically to stimuli distinguished by pitch, loudness, and length with comparable results in different studies. If subjects respond selectively to stimuli, Nd can be demonstrated under a wide range of conditions.

Näätänen (1982) proposed that Nd depends upon selective rehearsal of a memory trace for some combination of target features that aids in selective responding. The trace is hypothesized to require both recent afferent and efferent support for its maintenance, decaying on the same time frame as sensory memory. Therefore, most two-channel paradigms are thought to result in a trace which holds the attended channel, but not the deviant target characteristics. For example; the trace "remembers" the sound of tones in the attended ear, but not the difference between standards and the slightly higher pitched deviants. When each incoming stimulus is compared against this rehearsed memory trace, (which Näätänen calls an attentional trace) a match results in the early modality-specific component

of Nd, presumably generated in sensory and association cortices. The frontal late Nd is interpreted as either reflecting further processing after matching with rehearsed characteristics or as the rehearsal re-update itself. The characteristics that comprise the rehearsed trace are thought to correspond to the stimulus channel postulated by Broadbent (1970—see page 58).

It is important to determine whether a subtraction-derived attention-related ERP deflection is produced by increasing negativity in the attended channel, by decreasing negativity in the unattended channel, or both. Most authors have followed Näätänen in treating Nd as increased negativity in an attended channel. However, it is difficult to find an unobjectionable baseline from which to measure amount of processing in all channels.

Hink, Van Voorhis and Hillyard (1977) used a divided attention baseline (amplitude of N1 when the deviant stimuli in both channels were targets). They found the amount of N1 activity over a run to be conserved over divided attention and focused attention runs. That is, $\text{peak N1}_{\text{channel 1}} + \text{peak N1}_{\text{channel 2}}$ when both are simultaneously attended, was equal to $\text{peak N1}_{\text{channel 1}} + \text{peak N1}_{\text{channel 2}}$ when each channel was attended alone. However, total N1 was lower in a passive read (and ignore the tones) condition. Using N1 amplitude as a measure of attention, they reported both increased activity in attended channel and decreased activity in unattended channel, as compared with baseline. Aine & Harter (1984) reported the increased selectivity of the left hemisphere in the processing of colors to be due to both left hemisphere increased ERP activity to attended stimuli and decreased responsiveness to unattended stimuli. Moreover, the superior left hemisphere processing of Stroop color names was shown to be primarily due

to decreased responsiveness to unattended stimuli. Gaillard and Verduin (1985) found suppression of early ERP processing with inattention. These studies support a view of Nd as a sign of intraperceptual filtering (see page 61).

Some authors have attempted to explain the Nd data by postulating that it represents not one selection process, but a number of serial and parallel selection operations. Harter and Guido (1980) show one negative deflection related to the presence or absence of a visual grating and another for orientation of grating. When the target had no grating, the negativity representing orientation selection did not appear, since the first operation was sufficient to determine target membership. Hansen and Hillyard (1983) supported sequential operations within auditory Nd. Stimuli that could be classed as nontargets on the basis of an easy to discriminate characteristic did not show ERP differences due to a more difficult attribute discrimination. By manipulating the difficulty of the discrimination, the order of analysis of location and pitch information was apparently reversed. This contrasts with one notion of visual Nd selection, where a sequence has been proposed stretching from location selection (about 100 msec), contours (130 msec), color or spatial frequency (150 msec) to orientation (200 msec) (Ritter et al. 1984). While the onset of the different selection processes may be invariant, feedback from quickly analyzed easy attribute discriminations could be used to shut down further processing. Hillyard and Munte (1984) found selection on the basis of location of colored bars preceded location by color. If the locations were brought closer together, a point was reached where the attenuation of color processing vanished, and both attributes showed ERP differentiation. The fact that an attribute can leave no ERP signature if another attribute makes it task-irrelevant implies

that while selection mechanisms may analyze different features in parallel, feedback from these analyses can affect subsequent operations.

Harter and Previc (1978) used eight different check sizes to show a progressive fine-tuning of attention that narrows to the specific target until the approximate time of motor response initiation. Their attempt to relate the ERP size selection effects to size-specific aggregates of cells in visual association cortex is consistent with cell-assembly theory (Hebb 1949-see page 50). Moreover, in conjunction with Hillyard's identification of Nd with stimulus-set selection, and the Allport et al. (1985) suggestion that early selection may be a sign of selection by attributes coded in topographic brain maps (see page 65), it suggests that the internal templates associated with Nd may need a certain innate level of cortical organization.

One early negativity has been shown with semantic stimuli. Ritter, Vaughan and Simson (1983) report on a series of experiments where a simple RT task with an invariant stimulus was contrasted with a disjunctive choice RT task where the same stimulus was presented on 80% of the trials. If the ERP produced by the 100% stimulus is subtracted from that produced by the same stimulus as an 80% event, an early negativity is superimposed over the exogenous N1 deflection. The component, designated N_A , was recorded for three levels of stimulus complexity from a simple bracket (where the 20% event pointed in the opposite direction), to visually presented male names (where the 20% category were female names). N_A onset did not change, but peak latency increased with stimulus complexity, and when stimuli were masked.

Although the highest level of complexity required semantic analysis (male vs. female names), it is important to realize that N_A does not

represent a differential operation dependent on early analysis, as does Nd. The subtraction made is between runs using different instructions, and therefore likely to represent an operation applied to all stimuli in the choice RT run. The authors propose that N_A indexes the greater amount of a pattern recognition operation that is needed in choice RT. N_A consistently showed largest amplitudes over T5, consistent with a source in the inferior temporal area, where single cells have been shown to discriminate with attention (Moran & Desimone 1985). Also, when going from two to four targets, the 35-45 msec increase in the time needed to reach the level of completion of N_A necessary to release the following N2, is consistent with the 17 msec per target needed for focused attention in Savi and Julesz (1985).

Probability and Attention

Näätänen (1982) has pointed out that the subtraction waveforms that usually operationalize Nd define the processing differential rather than the total processing negativity. In other words, there will be some processing of even "unattended" channels. At some point, depending on the separation between channels, unimportant channels will be discriminated and "drop out".

A pilot study used three pitch channels to look for gradations in Nd (Berman, unpublished). Only the extreme pitches served as attended channels. While the expected Nd differences were generally recorded using tones of .5, 1 and 2 kHz, some participants reported the middle tone seemed closer to the low tone. This subgroup had less Nd for low tones than high tones. For the last participant, the middle pitch was made closer to each of the extreme pitches in turn. Subtraction Nds (as attended standards minus

same tones as unattended standards) were obtained for .5 and 2 kHz standards using a middle channel of 750 Hz and again using a middle channel of 1.5 kHz. Normal Nd appeared in the channel easy to discriminate from the other two, but there was little or no Nd in the channel that was difficult to discriminate from the middle channel. Since the distance between the two potentially attended channels (.5 and 2 KHz) was not changed, the unattended extreme should "drop out" of processing at the same point, regardless of the difficulty of discriminating the middle channel. While these results are currently unexplained by the attentional trace theory, they are consistent with the use of a variable strategy based on what the listener expects each new event to be. If the attentional trace is a cognitive tool, how might its application be affected by presenting categories of events with unequal probabilities?

It has been shown that endogenous ERP components depend on the category in which events are subjectively assigned, rather than the objective characteristics of the eliciting stimuli (Friedman et al. 1975). Johnson and Donchin (1980) used equal probabilities of 1, 1.4 and 1.8 kHz tones, where the task was to count the 1 kHz events. They demonstrated that the sequential effects on P3 amplitude of the nontargets was approximately the same as when target 1 kHz tones appeared with a probability of 1/3 and the remaining 2/3 of the tones were all 1.4 kHz. Since P3 to a 1.4 kHz tone did not change when probability was changed from .67 to .33, they argue that in both cases, the 1.4 kHz tones were assigned to a .67 probability class of nontargets. Although their three tones are objectively equidistant, the characteristics of the human nervous system makes the subjective difference between 1-1.4 kHz larger than 1.4-1.8 kHz.

If their thinking is correct, the unequal distance of the middle tone in my final pilot subject should cause her to assign the same 1/3 and 2/3 categories when the attended channel is the easily discriminated extreme. However, what happens when the attended channel is the extreme pitch close to the middle tones (attend .5 KHz with a middle channel of 750 Hz, or attend 2 KHz with a middle channel of 1.5 KHz)? It may be the fastest strategy to assign all incoming events to a 2/3 probability category of potentially interesting tones, and a 1/3 probability category of events that can be quickly rejected from further processing. A later discrimination between attended channel tones and middle tones would be more effortful, and those resources could be conserved for 1/3 of the tones by the establishment of this expectation for "highness" or "lowness". In other words, the ease of discriminating tones may control the assignment of various tones into different categories, regardless of the attended stimuli. A preset expectancy for the most probable category will enable saving of further processing resources on the majority of events if the targets are in the minority category, and saving of the resources needed for a difficult discrimination on many events when targets are in the majority category. If all channels are phenomenologically equidistant and equally probable, there is no savings for grouping channels, and the only type of "expectancy" that will be generated is an attentional trace of the tones of greatest interest.

This explains why Nd is seen for standards as well as for the rare targets themselves. If an expectancy establishes an internal representation which is automatically compared against all incoming stimuli in order to tag a category of events which require further processing, it will be used to separate the "attended" channel events from all other events. If all channels are equally probable and equally discriminable, greater negativity will be

seen for all attended channel events. If channels are not equally probable (or not equally discriminable such that they may be grouped into nonequally probable categories) there will be greater negativity for all high probability classed events, and negativity due to further controlled processing of stimuli tagged as requiring further processing. Because the negativity that represents comparison of the incoming event with the expectation is preset, whereas only the further processing is stimulus controlled, there may be a savings in resources even when there is not a savings in negativity. In other words, I think there are negativities due to automatic processes that do not compete for the limited pool of processing resources used by conscious attention.

It is certain that the motor potentials associated with limb movement would be recorded while one was driving home on "automatic pilot". But these negativities do not interfere with a train of thought until an unexpected event causes one to move the wheel consciously. There are limits to what processing can be automated, but practice enables finer discriminations. "Breakthrough" of your own name at a cocktail party (hearing your name in an unattended conversation) shows that tagging of complex stimuli can be automated. Finding out how widely attentional breakthroughs would generalize to similar sounding words would allow quantification of just how finely tuned automatic attention can be. A highly practiced subject may not require the one-minute build-up period ascribed to the processing negativity, and may not generate as much processing negativity to standards under certain conditions. As long as a standard is more probable than a target, it will provide a differential expectation. However, if targets are more probable, there may be little processing negativity for easily discriminated standards. Even with rare targets, more

easy to discriminate standards will generate less of the portion of Nd representing further processing. This is consistent with the results of Parasuraman (1981) who found greater amplitude Nd with a more difficult within-channel discrimination.

This view predicts that channel probability will be an important determinant of processing negativity. Just as the three-channel pilot showed little processing negativity difference between attended target standards in a high probability class and the same standards when that class did not contain targets, so a high probability channel in a two-channel design should show little Nd. In both cases, the expectation-matching negativity will be generated regardless of "target" channel, and may mask the processing negativity that occurs when the high probability channel contains the targets (the subtraction of unattended standard from attended standard will be small). On the other hand, a low probability channel will show no negativity when unattended (fast rejection of the need for further processing and no reason to maintain an internal template), and will show processing negativity only when attended. The maintenance of the internal template in low probability channels is inconsistent with the decay time proposed by Näätänen (1982).

Also, current views regard processing negativity as insensitive to manipulations of probability (Gaillard & Verduin 1985, Ritter et al. 1984). If we examine the evidence, the consensus is based on manipulations of target probability within a channel. As long as standards are more frequent than targets, I would not expect this type of probability to influence Nd. Could the use of equal probability channels have hidden the effects of channel probability?

In order to test the prediction of channel probability effects on the amplitude of N_d , a two-channel systematic manipulation was designed. Since the observations that prompted this experiment involved the purported collapsing into one category of two of three equally likely information channels (resulting in small N_d), it was specifically hypothesized that channel probabilities of .67 or higher would produce lower amplitude N_d than equal probability channels.

METHOD

Subjects

Eleven normal volunteers (7 male, 4 female) aged 20-47 served as research participants. All volunteers reported no hearing problems. All were able to relax enough to limit large artefactual potentials to less than one in four ERP single trials. Three additional volunteers did not complete the experimental paradigm because of excessive levels of movement artifact or inability to make the auditory discrimination.

Stimuli

Each run consisted of 250 tone bursts at a regular rate of 1/1.25 sec presented binaurally through Amplivox Audiocups. Tones varied in both pitch (low=500 Hz, high=1,000 Hz) and plateau duration (40 msec standard tones and longer tones that were adjusted for discrimination difficulty at the beginning of each session to between 60-90 msec). All tones had rise/fall times of 9.1 msec and were presented at 40 dB for high tones and 45 dB for low tones. In this way, subjects reported phenomenology of equal loudness of the two pitches, which will hereafter be referred to as channels.

Nine per cent of the tones were randomly occurring long tones, with approximately 4 per cent long high tones and 5 per cent long low tones. The relative proportions of standard high tones and standard low tones, comprising the remaining 91 per cent of the tones, were assigned according to the experimental condition of each run. The seven levels of channel probability tested ranged from 30 per cent low tones/70 per cent high tones, to 90 per cent low tones/10 per cent high tones, in increments of ten

per cent (30/70, 40/60, 50/50, 60/40, 70/30, 80/20, 90/10). All stimuli were selected by the pseudorandom number generator of the Pathfinder II (Nicolet Biomedical). The distribution of stimuli varied from the assigned probability level by no more than plus or minus 3 per cent overall. For example, the probability of high tones in the 50/50 condition was actually close to 53 per cent over all participants.

Recording System

Event related potentials were recorded from silver-silver chloride cup electrodes at Fz and Cz of the International 10-20 system (Jasper 1958). These locations are 30 and 50 per cent of the nasion to inion distance, respectively. Both electrodes were referenced to the tip of the nose. A forehead electrode served as ground. All electrode sites were abraded before application of electrolyte and inter-electrode impedances were kept below 2 Kohms. Potentials were amplified with Nicolet SM 200 physiological amplifiers and averaged online into separate memory bins according to the electrode site and type of tone (Fz or Cz electrode x high or low tone x standard or long length = 8 bins). Bandpass was .5 to 40 Hz using 2-pole Butterworth filters. Event related potential recording digitized each sweep into 512 points beginning 80 msec before each tone and continuing for 800 msec. An on-line artifact rejection system excluded sweeps with any voltage after the first 80 msec having a real value greater than 48 μ V. At the conclusion of each run, all bins were corrected to a baseline by subtracting the mean prestimulus voltage from each data point in order to minimize the effect of DC shifts. All waveforms were stored on floppy disks.

Procedure

Each participant reclined in an easy chair inside an electrically shielded room. Subjects were told that they would be counting occasional slightly longer tones in a given pitch channel. Before the first auditory attention run of each session, participants practiced detection of longer tones, in each channel separately, for between 5 and 14 minutes.² During practice, tapping signaled long tone detection. Duration of longer tones was manipulated until detection between 75-95% was achieved. All subsequent runs in the session used this duration value.³

Seventeen runs, over two sessions, constituted the experiment proper. There were three sets of instructions; count low, count high and read. During each counting run, participants were instructed to listen carefully for tones in the attended pitch channel, and to silently count the long tones (targets) in that channel. Number of targets counted was reported after each run. Eyes were either closed or focused on one spot, while all muscles were kept as relaxed as possible. Most participants reported better concentration with eyes closed, although the soporific nature of the task caused some participants to occasionally open them to keep awake.

Instructions for the "read" condition runs were to search a grid of letters to find as many as possible of a given list of words embedded in the grid. Participants were instructed to minimize eye blinks and muscle movements, and to ignore the tones.

²If the first scheduled run of a session was a read run, the tone discrimination practice was given after the first run.

³ In one participant, poor detection performance required lengthening of the long tones mid way through the first session. Some participants needed a more difficult duration discrimination on the second experimental day.

At the conclusion of each run, the experimenter asked for the number of targets detected (long tones or words). The run was repeated if the online artifact rejection system (see page 22) rejected more than 25% of delivered tones, or the participant reported falling asleep.⁴

There were 9 runs on the first experimental day and 8 on the second. Fourteen of these consisted of an attend high and an attend low run in each of the seven conditions of differential pitch channel probability. Eight of these were administered on the first experimental day and 6 on the second. In addition one "read" control run was administered on the first day and two on the second. The three read control runs used the pitch channel probability conditions of 30/70, 50/50, and 70/30.

The read control runs were administered at the beginning or end of a session, counterbalanced between subjects. The seven probability conditions were also counterbalanced between subjects for order within a session. The two counting runs in a single probability condition were administered in sequence and each condition that began with an "attend high" run was followed by a condition beginning with an "attend low" run, and vice-versa, resulting in an ABBA pattern.

Short breaks were given between runs with longer breaks between conditions, when needed to maintain wakefulness. Most participants had a cup of tea or coffee during one break per session. Depending on the number

⁴ After the first few sessions, it became clear that lapses of attention sufficient to cause large decrements in performance were not always reported. If asked why the count was so far off, participants sometimes reported "nodding off", but thought it was just for a second. After this was realized, a run was also repeated if number of targets detected was incorrect by more than 6 units. Four individual runs exceeded this level of error before this criterion was adopted. They could not be repeated without confounding the run order variable.

and duration of breaks requested, and the number of runs conducted, individual sessions lasted 2 to 4 hours.

Eye-Movement Control

After the completion of all formal runs, it was decided to record the processing negativity with an electrode adjacent to one eye in order to further control for the effects of ocular potentials. Although the online artifact rejection system will catch most of them, the large amplitude potentials that accompany eye movements are a potent source of artifact. Four volunteers were tested with various parametric changes, which were made because the addition of the ocular site raised the artifacting to unacceptable levels. The adjustment of the rejection level in particular, (from 48 to 96 μ volts), makes this data difficult to interpret. The fifth ocular control subject (EN) was able to maintain very low artifacting with the sensitivity setting (48 μ volts) used in the body of this report. Electrodes were placed at Cz and under the right eye, with both referenced to linked earlobes. In this way, any vertical eye potential will be recorded with opposite polarity in the two records. Subject EN was tested with the same counting instructions as the experimental subjects in four conditions of low/high tone probability; 50/50, 80/20, 10/90, and 50/50 again.

RESULTS

Standard Tones

The grand mean ERPs for 40 msec standard tones at all channel probabilities are presented in figure 2. A negative deflection at about 100 msec (N1) was followed by a positive deflection around 200 msec (P2) and generally by a later positive deflection (LPC), (see figure 2, Appendix B). Normalized difference waveforms were generated by subtracting the record of unattended standards from the record of the same events as attended standards. (Whenever subtraction waveforms are used, the raw waveforms will be included to allow more complete examination of the source of the subtraction differences.) Nd was quantified as the negative area from 80-480 msec (see figure 3, Appendix B). Shaded areas show the greater early Nd at the Cz electrode, but greater late Nd at the Fz electrode.

The major finding of this study is that the predicted decrease in the amplitude of Nd with high channel probabilities was confirmed. Since the prominent Nd peak occurred at about 240 msec, peak amplitude prior to 320 msec was graphed as a function of channel probability for both standard tones at each electrode site (see figure 4, Appendix B). It can be seen that the usual equal probability condition for Nd generation lies in the center of a plateau. Not only do high probability channels show the predicted decrease in Nd, but low probability channels appear enhanced.

The predicted finding was confirmed by Wilcoxon T-test of the difference negativity from 80-480 msec (Nd), using the individual subjects as the unit of analysis as follows. Since there were no noticeable differences due to pitch of standards, the grand mean of all standards with probabilities 10-60% was compared with all those with 70-90%

probabilities (see figure 5, Appendix B). An Amsler polar planimeter (Kueffel & Esser model 620000) was used to measure the area of Nd for all subjects in the 10-60% and 70-90% probability conditions in the individual grand mean difference waveforms that summed to produce the lower panel of figure 5. The data was analyzed by a nonparametric Wilcoxon T-test, as a conservative measure to protect against a violation of homoskedasticity. (Although all waveforms are made up of individual trials, high probability channels would have larger numbers of events in each run, and smaller variability in the run averages.) Ten out of eleven participants had smaller amplitude processing negativities at high probabilities and the difference was statistically significant, (Wilcoxon $I_{Cz}(10) = 2$, $p < .005$, $I_{Fz}(10) = 8$, $p < .025$), see Table 1, Appendix B.

To examine the development of this effect over time, the Nd period was broken down into 80 msec bins, and Nd area measurements were compared for the two probability groupings in each bin (10-60% vs. 70-90%). A computer program which measures the area below the baseline for any given time segment of a waveform was used (Int on Extended Library, Pathfinder II, Nicolet Biomedical). This method of measurement gave results comparable to those of the polar planimeter for total Nd of the first participant (see table 1, Appendix B). Because it is difficult to use a polar planimeter accurately for small areas, only the computer measure was taken for the 80 msec bins. Only the two bins from 160-240 ($I_{Cz} = 0$, $I_{Fz} = 6$) and 240-320 msec ($I_{Cz} = 4$, $I_{Fz} = 8$) had significant Nd decreases with high channel probabilities ($p < .025$, 1-tailed). In both bins, the Cz effect was greater. However, in grand means (see figure 3) and in 10 of 11 individual subjects ($p = .006$, 1-tailed Binomial Test), early Nd appears greater at Cz but late Nd appears greater at Fz, consistent with the

customary separation into an early posterior component and a late anterior component.

Use of the more sensitive parametric t-test allows visualization of this effect over the entire recorded timebase (see figure 6, Appendix B). The 720 msec of ERP following the tone was divided into 80 msec sections for each subject. A separate t-test of the area of 10-60% channel probability Nd vs. 70-90% channel probability Nd was conducted for each electrode in each time section. All results are graphed in figure 6, with important values for t ($N = 11$) shown on the ordinate. Note that while the major effect of channel probability on Nd area takes place from 160-320 msec with Cz greater than Fz, there is a later effect which reaches significance only at the Fz electrode. In retrospect, it may have been unwise to operationalize Nd as completed by 480 msec.

As mentioned above, negativity in a subtraction waveform can result from increased negativity in the base waveform, or increased positivity in the one subtracted from it. A diminution in subtraction negativity, such as the one seen in figure 3 for high probability channels, could result from the inverse of either effect. The raw waveforms for probabilities 50 through 70 were examined to determine which effect caused the change in processing negativity first found at 70% channel probability (see figure 7, Appendix B). For both pitches, the change is a consequence of greater negativity in the Nd range of high probability unattended channels. This processing-like negativity causes the attended-unattended subtraction to show little Nd for high probability channels.

In addition to the predicted diminution of Nd at high channel probabilities, there were indications of two other effects of channel probability. First, Nd appeared to be larger at low probabilities than in the

usual equal probability situation (see figure 3, Appendix B). Peak Nd was greater for the 10% channel probability than for the 50% channel probability condition for the high tones of all eleven participants at both sites. Twenty percent high tone standards had greater peak Nd than in the 50% condition for nine of eleven participants at both sites.

Additionally, all but two participants showed an early attention related positivity prior to Nd with high probability channels (see figure 8, Appendix B). One of the two participants who did not show this effect was MS, the only participant with no high probability Nd diminution. The other was RR, who fell asleep during several runs, and showed minimal probability effects. Only 2 participants showed this pre-Nd positivity with 10-60% probabilities. This attentional positivity may continue into the Nd range, thus contributing to the smaller Nds found with high channel probabilities. The pre-Nd positivity can be seen in 3 of the 4 high probability grand means in figure 3; high 70, low 70 and low 80%. There is no pre-Nd positivity in the low 90% grand mean.

Long Tones

The effects of attention and channel probability on the event-related potentials of long deviant tones produced more complex and less reliable waveforms (see figures 9 and 10, Appendix B). It is important to realize that each waveform shown in figure 9 averages the electrical response to between 89 and 152 tones over 11 participants. With less than 10 tones for some individuals in many conditions, the within and between subjects variability was so high that statistical comparison across subjects would be misleading (see figure 11, Appendix B). However, some points can be made from the grand means.

First, it is clear that processing negativity was reliably recorded for the deviant tones. Second, there appears to be a trend toward decreased Nd at high channel probabilities (with the exception of 90% low) and increased Cz Nd at 10 and 20% channel probabilities, replicating the pattern seen more clearly with standard tones.⁵ Third, there is more positivity in the P300 range than in standards, particularly in the attended (target) condition, at the Cz electrode. This results in an attention-related subtraction positivity with Cz larger than Fz in all probability conditions except 10% high (figure 10). Fourth, following the P300 positivity, there is a persistent attention-related negativity across all probability conditions, with Fz greater than Cz. This effect, which will be referred to as Nd500, is not seen for standard tones, with the possible exception of the 10 and 20% conditions (see figure 3, Appendix B).

Read Control Condition

Read control runs used channel probabilities of 30, 50 and 70%. At 30 and 50%, standards looked similar to attended experimental runs with deeper N1s but without LPCs (see figure 12, Appendix B). At 70%, control standards were less positive than both attended and unattended experimental standards during the peak Nd latency range.

Long deviants showed a similar pattern in control runs, with more variability and late positivity (see figure 13, Appendix B). They did not feature the late negativity which produced Nd500 in target deviants.

⁵Measuring at Cz, Nd peak amplitude for 70% and 80% low deviant tones show less negativity than in the 30, 40, 50 and 60% conditions. Likewise, 70% high deviant tones have less Nd than all other high deviant probabilities. Low probability channels (10 and 20% high tones) show more deviant Nd than in higher probability conditions if total area is measured, rather than peak amplitude.

Butler (1968) has shown pitch-specific refractory effects on ERPs. Subtracting the 70% from 30% standards shows a consistent 1-1.5 μ V effect of frequency on the exogenous deflections (see figure 14, Appendix B). Low standards also showed a slow late positivity in comparison to the other conditions.

Ocular Control

Participant EN demonstrated the Nd attention effect for standard tones without recording reverse-polarity potentials in the eye channel (see figure 15, Appendix B). Most potentials recorded under the eye were much smaller, and of the same polarity, as concurrent Cz potentials. The only sizable eye potential (10% low tones) was also of the same polarity (negative) as Nd, consistent with a cerebral, but not ocular source. The effects of channel probability can be seen by comparing the amplitude of Nd in high and low probability channels. They are consistent with the grand means and show no contamination by eye-movements, which would have been reflected in opposite polarity differences at the eye site.

It may be instructive to compare the ERP records of the identical first and last runs. In the final run, both high and low tone unattended P2 were more positive than in run 1. This is consistent with a "better rejection" interpretation for ENs report that she felt she was accomplishing the task better at the end than at the beginning of the session. EN also reported that low tones were more difficult to count, and her counting performance was consistent with her subjective assessment. When high tones were counted, P2 (the area of greatest Nd) became more positive over runs, but the reverse was true for attended low tones. This is consistent with an "effortfulness" explanation, as if the second pair of equal

probability runs featured less effort (and less processing negativity) when the easy channel was attended, but more negativity when the difficult channel was attended.

DISCUSSION

The prediction of low Nd when channel probability is high was confirmed. How should this be interpreted? Since figure 14 shows frequency specific refractoriness in control runs, could this be responsible for decreased Nd to high probability stimuli? There are two reasons why this factor must be considered vanishingly small. First, the Nd waveform represents a subtraction between two series of events with the same frequencies and probabilities. Only the attention instructions varied. Refractoriness effects should be washed out by the subtraction process.

Second, figure 7 shows that the major effect is a function of increased negativity in the unattended channel. It represents an abrupt change from 60% to 70%, rather than the gradually smaller P2 expected with increasing refractoriness. In contrast, the visual attention controls showed most refractoriness between the 30 and 50% conditions. P2 was actually larger in 70% than in 50% ERPs to control low tones, and high tone P2 was only .5 μV smaller at 70% than at 50%. The much larger change from the 60 to the 70% condition for both pitches when unattended must be due to the stimuli being processed differently when they are task-relevant.

While I would like to interpret these findings as support for the theoretical framework presented in Appendix A, some limitations of this experiment, which will be discussed below, make it premature to make an assertion of that specificity. Other cognitive interpretations must be ruled out. However, these findings can be interpreted as representing some change in the strategies used to process information.

The finding of high amplitude Nd in low probability channels (in the 10% condition, attended channel events had mean interstimulus interval of

12.5 seconds), indicates that any attentional trace is more durable than proposed by Näätänen (1982), or is used in a different manner.

The finding can not be due to rare events producing the part of N2 called mismatch negativity (MMN-Näätänen et al. 1978), since this is postulated to be an exogenous response to deviance, and should subtract out of the Nd subtraction waveform. While most laboratories now discriminate between this exogenous part of N2, (often labelling it N2a), and an endogenous N2b (Näätänen et al. 1982), if the Nd in low probability channels is actually due to N2b being generated only when the low probability channel is attended, it is suspicious that topography and shape of the Nd effect should so mimic the Nd seen in higher probability channels. More important, if N2b becomes prominent in attended low probability channels, we should expect to see the other components of the triphasic complex postulated by Näätänen and associates (1982), P2b and P3a. In fact, figure 4 shows a possible attention-related positivity prior to Nd only in high probability channels, and there is no Fz-maximal P3a attention effect in any condition. A larger topographic array would help to clarify the extent to which N2b effects may contribute to these findings, but it is unlikely that they are responsible for the congruent but larger peak Nd recorded in low probability channels (see figure 3, Appendix B).

Näätänen (1982) speculates that the attentional trace might be a neuronal facilitation pattern in secondary sensory areas. After sensory decay, he states that only a more frontal cognitive representation remains. This trace is thought to use verbal mediation, (since it lacks perceptual attributes), and is too nonspecific to aid performance. How are Nd and performance maintained in low probability channels? Why is posterior

predominance of peak Nd at least as strong in low probability channels as in equal probability channels?

One possibility that explains both large low probability channel Nd and small high probability channel Nd is that the attentional trace can be applied to the high frequency irrelevant standards when the "attended" standards occur too infrequently. Since there is generally little difference between the two standards, an internal representation of one might aid in "refreshing" the internal representation of the other. For example, both standards had the same rise/fall times. Both were pure tones of similar intensity. Perhaps most relevant, both had equal durations. Duration information is important in making the difficult within-channel discrimination between deviants and standards. The ERP result of this type of attention would not be expected to show discrimination in high probability channels. That is, subjects would apply the attentional trace to the high probability channel standards when that channel was attended, (for the usual reasons), and when the other channel was attended (in order to maintain the best perceptual approximation possible in the attentional trace). An attention subtraction waveform would show little Nd. Use of this strategy could produce performance superior to a strategy that allows decay of the attentional trace. We can be prepared for more than one event, relative to all other events.

A less parsimonious but compelling alternative explanation would attribute the extra negativity in the ERP elicited by high probability "unattended" events to a different process than that generating classical Nd. The fast decay rate of the attentional trace has been inferred rather than empirically measured (Näätänen 1982). If the internal representation does not decay quickly, the different pattern in high probability channels could

involve the confirmation of expectations about the nature of each succeeding stimulus (Squires et al. 1976). Human beings are not passive processors of information. They anticipate events, recreating their perceptual world constantly. It seems adaptive that when one pays attention to a sequence of two possible tones, and one predominates sufficiently, an expectation is generated that each next tone will be in the high probability channel.

Turning to the behavioral literature, we find many effects which support the concept of expectancy as a pervasive strategy. There is a long history of probability learning studies, which demonstrate that human beings are capable of precise probability discriminations even prior to adolescence (Gould & Goodwin 1970). The effect of foreperiod of a warning stimulus on RT to an imperative stimulus interacts with probability such that a high probability event is more impacted upon by a warning stimulus (Posner 1978, chapter 5). This makes sense if there is differential preparation for the high probability event. The effect which decreases RT with increases in stimulus intensity also shows less impact on low probability stimuli (Niemi & Keskinen 1980). However, this was only true if the task was not too easy. Likewise, I would not expect large N_d if both between and within channel discriminations were very easy, as there is no need of selective attention.

A warning cue that is highly likely to provide task-relevant information will facilitate task performance when it does provide information, and will inhibit task performance when it does not (LaBerge et al. 1970, Posner & Snyder 1974). Posner and Snyder used a warning stimulus that had 80%, 50% or 20% probability of being in the task array. When the task was to tell if a letter pair matched, the warning cue was the

matching letter on the given probability of "yes" responses. At 80% match, there was faster responding when the cue matched the target pair, compared to a control condition using a neutral (*) cue. There were costs of misleading cues in both RT and number of errors. For example, when the cue did not match a matching pair (b, aa) there were 30% more errors than in the baseline condition.

When the informative cue was an animal name, the same pattern developed for the task of deciding whether either of a subsequent array of two words was an animal name. When the animal name had an 80% probability of being the animal name in the task array, there was benefit if the cue was in the array, and cost if it was not.

In both letter and animal name conditions, the 20% cue matching condition showed benefit but no cost. The authors concluded that the participants matched the cue with the array only in the high probability condition, and benefited in some more automatic way in the low probability condition. Most participants tried to ignore the cue in the 20% condition. The only one who did this in the 80% condition was also the only subject to show benefit without cost of high probability cues! This is convincing evidence that we process information differently when there are cause for expectations about subsequent events.

Like the attentional trace of Näätänen (1982), a check of each incoming event against an internal representation may be involved in the current experiment. In fact, the generator could be anatomically identical, or different from that producing classical processing negativity. The difference in this view is that the mechanism is engaged by a probabilistic rather than motivational /attentional strategy. If there are two internal

representations or two ways of generating one, a ceiling effect may prevent their effects from being linearly additive.

In either case, the high probability events would show little or no Nd because extra negativity produced by a matching operation, (either due to confirmation of expectation or matching with an attentional trace), would be generated in the ERPs elicited by the "unattended" standards. There would be little difference between ERPs to unattended and attended high probability events, and thus a small Nd.

Both interpretations are consistent with the change in Nd from 60 to 70% channel probability resulting from greater negativity in the unattended channel at 70%. Therefore, the findings are interpreted as representing a changing pattern of adaptive cognitive strategies with sufficiently unequal channel probabilities .

Attention strategies are suggested by the observations of Posner (1978) that differentiate the effects of probe interference from cost of misleading cues. Facilitation due to pathway activation (such as use of the target letter as a warning signal) and interference from the surprise occurrence of a distractor probe begin immediately, and level off by 300 msec. Inhibition due to a mismatching cue (relative to a neutral cue) does not begin until 300 msec. More important, it only occurs when the probability the cue will match the target has been high. In one series of experiments using digit cues, the occurrence of this inhibition further depended on instructions to use the digit to improve performance, (rather than to use it as a warning signal). This clearly relates inhibition to a controlled strategy which processes the cue differently in order to maximize performance. The interference comes not from the objective characteristics of the event, but from plans as to how it is to be used. The

timeframe is similar to the late component of Nd, which the model presented herein attributes to cognitive feedback on the significance of an event in frontal executive centers. With less predictable primes, the more variable pattern of facilitation and inhibition have been interpreted as representing participant experimentation with different controlled attention strategies (Posner 1982). The strategic nature of these results were underscored by occasional participants who reversed overwhelming trends in the effect of probability of prime match. Participant MS (the only subject showing no channel probability effect on Nd-see figure 8, Appendix B) showed the same reversal in the current study.

Two additional speculations may be made as to why MS does not show the pattern found in all other participants. First, he is lefthanded. Sinistrality has been associated with higher incidence of uncommon types of hemispheric specialization, which could have far reaching implications for attentional strategies. More striking is the fact that he misunderstood the instructions and was using small finger motions to keep count in all but the last two runs. This strategy obviates the need to maintain a record of the current count, since one can check the fingers at run completion. It makes the task much easier, introduces the possibility of motor artifact, and may relate to other strategic changes in signal processing. Additional information on the individual participants is presented in appendix C.

Larkin and Greenberg (1970) have discussed the concept of listening strategies in frequency detection tasks. They suggest the effect of different presentation probabilities may be to make the listener a more efficient recognizer of higher probability signals. The question remains as to why the channel probability function shows a discontinuous jump between 60 and 70%.

Estes (1984) has concluded that human choice behavior is controlled by a mixture of local feedback and more global information encoded in abstract memory. Probability learning can usually be well explained by models emphasizing trial-by-trial feedback. However, such models shed no light on studies where performance rises above probability matching level. For example, when long series of trials consistently feature one of two signals 80% of the time, participants have shifted from probability matching (predicting that signal 80% of the time) to the more effective strategy of selecting the favored alternative more than 80% of the time. This supports the idea of global expectation for high probability events.

To test the idea that this shift was due to memory for global features, sequences where probability shifted in a sine wave pattern during the course of each block of trials were followed by blocks where the two alternatives occurred randomly. In the early blocks, event A started at high probability and decreased in frequency through the block. Event B rose in frequency reciprocally. While probability matching theories predicted the pattern of choices in the sine wave trials, it could not account for the maintenance of the sine wave pattern after the blocks became random.

Estes theorizes that in any uncertain situation, humans automatically encode event probabilities, but also store other relevant information "salient enough to be encoded and rehearsed". Once both local and global representations have formed, the learner can develop strategies that shift control of behavior back and forth. This view easily accommodates the current findings, but still does not explain the conservatism of not applying the global strategy until encountering a 70/30 or greater split.

A study of tennis playing strategies may provide an answer (Proteau & Alain 1983). Positional shifts and RT were used to study how tennis

players improve their defense of areas of the court likely to be attacked. Participants had to move two meters laterally, with side of movement depending on which of two signals occurred. A warning cue gave the relative probability of the two signals. Rug sensors detected weight shift to either side between the cue and the discriminant event. The cue to target interval was fixed at 500 msec. Only when the specified attack probability reached 70% did participants initiate preparatory defensive strategies. The authors conclude that when facing event uncertainty, sports players do not tolerate risks well, and prefer reaction to anticipation. Their main concern is to minimize error rate, even when this is not the best strategy to use.

Is 70% probability another magic number ?? I don't think so. A similar experiment by the same group (Proteau & Laurencelle 1983) found a strategy of differential preparation at probabilities of 90% but not 70%, (although examination of their data shows a small change in the 70% condition as well). Many situational and dispositional variables are likely to influence the point at which an expectation-strategy is applied to a selective attention task. But a relative intolerance of risk could create a conservative application of these strategies, which would explain why the 60/40 probability condition shows the same ERP pattern as the random equal probability condition.

Other approaches to interpreting the effects of this study might look at motivational variables, within channel probability, vigilance, and component overlap. Donald and Little (1981) manipulated target probability within a channel from 6 to 25% and showed a positive correlation between target probability and N1 amplitude in standards. Interpreting this as due to Nd creates an alternative explanation for the findings being discussed. Since target probability was always about 4.5%, the relative target

probabilities within a channel ranged from 4.5/90 to 4.5/10. Donald and Little speculate that greater motivation to pay attention to a channel when more of the channel represents targets may explain their finding.

Certainly, motivational variables must enter into strategic planning. One of the most puzzling aspects of this study is the somewhat attenuated channel probability effect in the 90% condition. While there is less Nd difference than in the channels with probabilities 10-60%, one would expect that the high probability effects would be strongest here. Instead, they are weaker than in the other 3 high probability conditions. This may be due to an error on the part of the experimenter. Fearful of sleepiness in this most boring condition, I usually said something to the effect that these runs were the most difficult and if the listener could try hard to pay attention, the rest would be easier. In retrospect, this practice may have changed motivational level, or even directly altered listening strategy.

A related issue deals with the relevance of vigilance research for this paradigm. High frequency vigilance runs have shown decreases in sensitivity over time, (measured by d-prime), while low frequency vigilance tasks show stable sensitivity, but an increasingly conservative criterion to act on any stimulus, associated with increased sleepiness (Posner 1978, Ch 5). Considering participant reports of sleepiness toward the end of extreme probability runs, one might associate a high probability attended channel with high frequency vigilance and the low probability attention runs with low frequency vigilance tasks. Lowered ERP signs of selective attention are then consistent with vigilance research. If one considers a large P2 in "rejected" channels to be a major sign of selective strategies, (consistent with the small P2 in control runs), the loss of this effect in high frequency unattended channels is not surprising.

Another way of interpreting figure 6 sees one component which is maximal at Cz. The diminution of the effect that begins in the 320-400 msec bin could be attributed to overlap between Nd and the P300 component. Since P300 is also larger with attention, it will show up in the subtraction waveform. Since it increases with rareness, it will favor low probability channels. Even though some other factor appears to be increasing late Nd (possibly the endogenous portion of N2) in low probability channels, it may be opposed by attention related positivity. Since it is largest at posterior sites, it will diminish the Cz processing negativity measure far more than the Fz measure, allowing late bins to reach significance only at the less impacted site.

The trouble with accepting a within-channel probability motivational interpretation is that if it does not lead to different cognitive strategies, it cannot explain the discrete jump from 60 to 70%, nor why the effect is found only for the unattended high probability events. The vigilance findings may be relevant, but they do not constitute an explanation. Until the cognitive mechanisms at work are better understood, strategy changes seem a likely candidate for mediating vigilance effects, as well as the current channel probability effect.

The P300 explanation of figure 6 also does not account for the discontinuous change in Nd between 60 and 70%. However, this is a type of analysis that is generalizable to most ERP studies.

For example, in Fitzgerald and Picton (1983) the more frontal N2 to standards in the attend condition is attributed to the effect of those standards which required further evaluation, in order to be correctly classified. This need for further attention is thought to activate a more frontal processor which is identified with the N2b ERP component.

Summation of exogenous and endogenous N2s results in more frontal distribution than when attention is not required.

However, another likely explanation is that an early P300 opposes N2 more for attention runs, and mostly at the posterior site. Similarly, reports of a general N2 amplitude increase with task difficulty could simply reflect less overlap with P2 due to later N2 latency. Care must be taken to specify the interactions of latency and amplitude ERP dependent variables. This requires knowledge of the underlying component structure of the ERP waveform. The difficulty of establishing component identity has been discussed above. An attempted solution to this problem is discussed below.

Having rejected these alternative explanations, how may we choose between the two strategy-based interpretations? Is the high probability Nd decrement due to an internal probability-based expectation or a shift to attentional trace registration of both standards? While both of these explanations are tentative, three important questions that may be asked are these: First, are the negative difference waveforms seen by subtracting ERPs elicited by unattended standards from those elicited by attended standards at extreme channel probabilities the same components as the usual equal probability Nd? Do high and low extremes yield the same component? Is the extra negativity in the ERP elicited by an unattended high probability standard (relative to a 50% unattended standard) the same component as that seen in the ERP elicited by a 50% attended standard (relative to that same 50% unattended standard)? Once again, this raises the question of how to establish component identity.

A modified replication of this study with a full array of electrode sites is being planned. This will allow the use of the basic approach of McCarthy & Wood (1985) with regard to scaling and analysis of topographic

data. Individual peak amplitudes will be scaled as a percentage of the amplitude where the largest deflection is recorded. Separate 2-way analyses of variance (ANOVAs) will compare each of the other negativities with 50% classical Nd across electrodes, using a correction factor (Jennings & Wood 1976). An interaction between electrode and subtraction condition will be taken to indicate that the deflections represent different underlying components.

Although a finding of separate generators between the negativities recorded in this study would allow us to choose between the two proposed strategy explanations, finding the components to be equivalent is not as conclusive. The generators would be expected to be the same if both negativities result from formation of the attentional trace of Näätänen (1982). However, they could also be the same if a probability-based expectation represented the important strategy change with extreme channel probabilities. Indeed, if there is an internal mechanism for lowering the threshold of selected cell-assemblies, it would be parsimonious for it to be used for various cognitive purposes, rather than through creation of separate generators having the same function.

It would aid in interpretation if sequential dependencies could be demonstrated. If attentional traces decay as proposed by Näätänen (1982), then the large low probability Nd must be formed through use of a different information processing strategy than in the equal probability condition. It would not be surprising if the addition of a new operation caused a delay in the Nd. Suppose the new attentional strategy with low probability targets involves 1) checking incoming stimulus against expected trace 2) paying extra attention when this is disconfirmed. When the high frequency event is in the attended channel, no extra attentional demand is anticipated.

According to the scheme of Rockstroh and associates (1982) less preparatory negativity will be generated under the latter conditions, similar to lower amplitude CNV on trials where a distractor between cue and stimulus is not expected. If both negativities represent attentional traces, then attention to a low probability channel must maintain two traces, where attention to a high probability channel needs only one. Less preparatory negativity will be generated by high probability standards when attended, as compared to when they are "unattended". This may account for the pre-Nd positivity in the high probability channels. It follows that there should be more preparatory negativity (resulting in more Nd) generated by the concurrent low probability channels when they are attended! This seems to be the case, both for the Nd timerange and the pre-Nd latencies around N1. Since the pre-Nd positivity is found prior to 80 msec in some participants, it has important implications for attention theory, and deserves serious experimental consideration.

And do the low probability Nds lag behind their equal probability counterparts? In fact, all four low probability conditions show peak Nds later than the corresponding 50% condition at both electrode sites. However, the small differences (mean = 18 msec) require further experimental confirmation to determine the reliability of this finding. It is promising that ocular control EN shows the same pattern. An alternative explanation might attribute the latency change to overlap with an attention increased N2b, but there are some problems with this interpretation (see page 34).

If the attentional trace is maintained by formation of a similar internal trace of the "unattended" high probability standards, than deletion of those standards should reduce performance measures. In the reported

experiment, as in most processing negativity paradigms, the difficult part of the task lies in making the within channel discrimination. If the extra negativity in high probability unattended channels is a separate process relating to expectancy, there is no a priori reason its occurrence should affect the attentional trace, or the performance it subserves. Therefore, one way to choose between the two explanations is to administer both one-channel and two-channel versions of an RT version of an oddball paradigm.

That is, subjects would receive one run identical to those described herein, and a second run where the unattended stimulus was omitted or its amplitude was reduced below the hearing threshold. It would be useful to compare RT and signal detection performance (within the attended channel) in the two runs. If the attentional trace view is correct, removal of the unattended channel should cause performance decrements only in one-channel runs with interstimulus intervals longer than about four seconds.⁶

This experiment is also being planned. The experiment will have better control than the current study of the difficulty of the experimental task. While the experiment being reported here varied the durations of each individual's deviant tones, the decision to use unselected subjects led to difficulty in stabilizing performance without an extra practice session. Task difficulty is one of the most relevant variables for individual strategy differences, and probably accounts for a great deal of the variance in the current data.

⁶ In the current experiment, negativity resembling processing negativity appeared for "unattended" standards when channel probabilities went from 60 to 70%. If this was due to decay of any internal representation limited to using the low probability standard, the important interstimulus interval is that within the low probability channel. For the 60/40 channel probability split (normal Nd), this value was slightly over three seconds, and for the 70/30 split it was slightly over 4 seconds.

Another way of testing the importance of the 70% change would be to vary the interstimulus interval. If the strategy change results from attentional trace decay, then different probabilities should develop the need for this strategy depending on interstimulus interval.

One further limitation of the current study involves the time constant that was used. It has been shown that P300 and slow wave components can be markedly attenuated using a high frequency bandpass of .5 Hz (Duncan-Johnson & Donchin 1979). This makes interpretation of the novel long-latency Nd500 found for deviant stimuli particularly difficult. Its latency is consistent with a motoric artifact, and this possibility must be carefully checked out. Should we interpret this additional negativity as a further matching with the target characteristics? If so, it raises difficulties for the attentional trace model. Then again, it may be more akin to a mismatch operation like the late negativity seen after semantically incongruous words (Kutas & Hillyard 1980). Whatever cognitive operations it represents, Nd500 looks suspiciously similar to the late Nd seen only for 10%, and to a lesser extent 20% standards. Latencies, relative electrode magnitudes and the low probabilities of the evoking events are all the same. This best supports a process of mismatch with neuronal models, when attention is being given to a sequence. It is important that there is no late negativity with unattended or control deviants.

Appendix A

A Framework for ERP Attention Effects

This experiment has followed from and is interpreted within a larger framework I have generated in attempting to integrate the endogenous ERP findings of the last 20 years with the work of other scientists who have studied attention. I hope that it will be useful to the reader to present this model, and the thinking that led me to formulate it, in terms of understanding my personal biases in designing and interpreting this experiment. Because much controversy has concerned the extent to which perceptual processing can be affected by attentional mechanisms, I will give my view of perception, and then summarize some of the relevant work on attention. Following this, I will briefly review the not previously discussed ERP work impacting on attention, and present my model for integrating these findings.

Perception

My view of perception stems from cell-assembly theory (Hebb 1949). Some theory of this type, where sequential patterns of reverberatory neuronal discharge become hierarchically associated, seems most consistent with the phenomenology of thought and the physiology of the nervous system. I feel that thought and memory require internal representations that must be originally based on sensory impressions. Cortical physiology has been shown to consist largely of complex re-entrant pathways featuring massive parallelism. For example, monkey visual systems have been shown to use a modular organization with separate topographic maps for orientation, size, movement, and perhaps for color and for feature combinations (Cowey 1985). All cortical areas are infused with short-axon inhibitory interneurons. An outside input is sufficient to

excite continued neuronal firing long after receptor stimulation has ceased. Assuming the central activity is capable of structural modification, repeated activation of subsets of cells could establish connective associations that represent internal representations of percepts, and at a higher level of organization, concepts.

The theory was sparked by the wish to understand how large portions of brain could be removed with little effect on intelligence test performance. Hebb reasoned that all anatomical areas were important in establishing patterns of connectivity, but not in the expression of later behavior demonstrating the learning. Since 1949, much has been learned about brain physiology. Hubel and Wiesel's (1962) demonstration of different categories of visual system neurons dovetailed nicely with cell-assembly theory. Simple cells are best fired by a particular feature, such as an edge with a specified slope and location. Receptive fields of these units are small, and show spatial summation of the effect of luminance on cell firing rates. Complex cells have larger receptive fields and get inputs from simple cells. Orientation information tends to generalize, but locus is less specified. More complex cell groups receive inputs from both types of cells, forming multiple brain maps (at least 13 in the cat and 6 in the rhesus monkey) that are sensitive to a multitude of stimulus properties (Lennie 1980, Cowey 1985). In this way, groups of cells can establish the cell assemblies that support higher orders of abstraction.

Despite the organization of the visual topographic maps, it is important to realize that higher order cell-assemblies are thought of as primarily diffuse networks in association cortices, such that any given unit may be recruited by many different assemblies. The flow of receptor stimulation is necessary to organize the patterned connections and to

maintain the sequential flow of thought. Attention is hypothesized to involve central support of some assemblies over others. Three series of experiments explored these propositions. First, it was shown that early perceptual experience in a number of species has disproportionate importance on the establishment of cognitive capacities (Hymovitch 1952, Thompson & Heron 1954). Secondly, it was shown that extensive perceptual deprivation disorganizes normal cognitive functioning even in adults (Heron 1957, Zubek 1969). Finally, it was shown that when an image was stabilized on the retina, parts of the image would appear to vanish, dependent on what was attended to (Pritchard, Heron & Hebb 1960).

Normal vision depends on the constant small movements of retinal images. It was assumed that when an input was maintained on specific retinal cells, that the disappearance of the image was due to neural fatigue. But images more complex than a straight line did not vanish as a whole. Parts would intermittently vanish and reappear; for example, the separate lines of a triangle. When the perceiver was instructed to pay attention to a specific feature of the image, it changed the order and duration of these changes. This result not only agreed with Hebb's view of attention, but for the first time showed that there are neural groups representing sub-units of images. Even so simple an object as a triangle is not perceived as all or none, but by the combined presence or absence of smaller units. This is strong support for cell-assembly theory.

Attention

How might instructions to attend change the activity of these cell-assemblies? Any effortful mental activity has been shown to be accompanied by sympathetic dominance usually interpreted as related to alertness (Posner 1978, chapter 5). With general arousal come inhibitions of heart rate, spinal reflexes, eyeblink and irrelevant motion, along with a negative DC shift in the EEG which will be discussed below. Microelectrode studies have shown that synaptic transmission of a firing neuron will temporarily facilitate further transmission (Douglas & Goddard 1975). This means that subsequent inhibitory processes may be important to turn off an individual assembly. Short-term memory probably consists of regular sequential activation and inhibition of sub-assemblies, rather than continuous reverberation of a single unitary assembly. If many patterns can be activated at the same time, whether in parallel or by alternating their component assemblies in a serial time-sharing process, it explains the relative insensitivity to order of encoding which is characteristic of human memory. Lower competition in recruitment of cells would explain the primacy effect in list learning. A relatively lower decay state in close temporal proximity to encoding would give a memorial advantage to the most recent items. Because recency effects are derived from temporal proximity in this view, it is not surprising that primacy effects are much longer lasting (Wright et al. 1984).

Recent microelectrode studies have delineated areas of the brain where visual attention influences cell firing rates. If monkeys are cued to attend to one of two locations where stimuli are being presented, certain cells show higher rates of firing in response to effective stimuli at attended locations than to the same stimuli at the same locations when they

are unattended (Moran & Desimone 1985). In striate cortex, where receptive fields are only .5-9°, monkeys could not learn to attend selectively if both locations were within a field. With locations in different fields, discrimination was learned but cell firing rates did not change. The first subset of cells which show the discrimination are units in prestriate area V4 having both attended and unattended locations within their 2-4° receptive fields. Attention training does not increase baseline firing rates. On this level, attention selects through attenuation of the response to unattended stimuli

After striate and prestriate cortex, visual signals activate units in the inferior temporal area. Here, receptive fields are at least 12 degrees in width, and may cover the entire retina. Attenuation of the response to stimuli at unattended locations continues in the same manner. Because of the wide receptive fields, virtually no cells respond well to unattended stimuli. The authors speculate that these cells, which are sensitive to orientation, color and size information may allow discrimination of the properties of visual stimuli.

The only other area of monkey cortex where neural responsiveness has been shown to vary with attention is the posterior parietal cortex (Lynch et al. 1977, Bushnell et al. 1981). Some units show enhanced firing when the attended location is within the neuron's field. Because of the wide receptive fields and lack of sensitivity to properties other than location, this is interpreted as reflecting a mechanism for direction of spatial attention, without attribute analysis.

Posner and associates have shown that a complex series of behavioral consequences follows presentation of a warning stimulus prior to a discriminatory stimulus. Fastest responses occur at cue-target intervals of

about .5 sec (Posner 1978, chapter 5). This is generally interpreted as representing the peak of the function of increasing alertness with time after a cue. Increased alertness shortens RT but does not aid discrimination, since errors also increase. If vision is centrally fixated, and the discrimination to be made is between right and left periphery flashes, a peripheral warning signal will give a reaction time advantage to the subsequent processing of a signal on that side (Posner et al. 1982). Even if the cue signal indicates that the following stimulus is likely to be on the opposite side, a same-side advantage is not reversed until about 300 msec. Facilitation of RT to probe stimuli at various spatial locations and postcue times supports a model where attention "moves" through visual space at a constant rate, without eye movement. When peripheral cues signal the same-side should be attended, there is an attenuation of facilitation at about .5 sec, relative to when a central arrow brings attention to the same peripheral location. In summary, it appears that any signal increases alertness. A peripheral warning stimulus also facilitates and then inhibits subsequent response to similar signals by an additional automatic mechanism, whereas a central cue shows only a later facilitation by controlled processes.

It is a reasonable hypothesis that the automatic facilitation and inhibition of a peripheral cue are produced by synaptic facilitation and neural fatigue within cell-assemblies. Preparation must represent some prior activity in or on the cell-assemblies representing expected percepts and responses. One useful technique for exploring the nature of a cue effect uses a second "probe" task inserted between cue and target. If the probe raises the RT to the target, interference is said to occur between probe processing and processing of the primary task. Some studies have found

interference only when probes demand responses similar to primary task responses, or when probes are presented close to the time of target presentation. These findings raise the possibility that interference, and perhaps preparation, occur only in the response production stage of processing. Attempts to clarify the meaning of probe studies by manipulating the difficulty of the secondary task have not been consistent. Different authors claim additivity, convergence and divergence of task effects (Posner 1978, chapter 6). Since the entire network is associative, instructions could activate partial coherence of assemblies, perhaps by disinhibition of control mechanisms. This would effectively lower the threshold of direct afferent support needed to establish an active assembly.

Understanding of attention may be clarified by consideration of interactions among the different effects. The improvement due to more optimal foreperiod duration (the cue to target interval) is additive with the early effects of making a cue predictive. This shows that information-bearing cues evoke two processing mechanisms in parallel. However, as cognitive complexity increases, additivity becomes incomplete, indicating possible interference in a limited-capacity competition (Posner 1978, chapter 5). Contrary to adults, children actually show slower RTs to familiar signals. This effect vanishes if alerting is held constant. Children depend on novelty alerting more than adults do. The mechanisms of alerting, which are primarily subcortical, and the cortical mechanisms of expectation can interact. Posner feels both effects can occur by automatic and controlled pathways, speculating that one of the reasons for the evolutionary development of consciousness was to allow the adaptation of useful learned patterns to new purposes.

This way of thinking can be applied to some recent data of Savi and Julesz (1985). Tachistoscopic presentations of a filled circular array of parallel diagonal lines held one to four targets. Any line in the grid was a target if it was vertical or horizontal instead of diagonal. Subjects reported location of targets just as quickly for four targets as for one. If required to report whether all targets had the same or different orientation, addition of both the third and fourth targets increased decision time by increments of 17 msec. This was interpreted as indicating that detection and localization are preattentive parallel processes, whereas category classification proceeds serially for even a single primitive feature. However, in two of the three subjects presented, time to detect is equal to the time to discriminate with two targets. Not only does detection proceed in parallel with classification of orientation, but the second deviant can also be classified as quickly as a single target is detected. Since I see detection as being likely to draw varying amounts of a limited resource pool for subsequent attribute analysis, it seems probable that a certain amount of attribute analysis can occur as a parallel (gestalt) process, with an overload point where processing derails to a serial mode. This can be explored by requiring classification of vertical, horizontal or different orientations by button press. If RT for one target is the same as two, it supports my view. If even single attributes must be processed serially, there should be a 17 msec difference.

Recent data on the physiology of attention must be interpreted in the framework of a large body of theoretical speculation. Broadbent sparked much of the modern interest in attention by proposing a buffer store where information on groups of stimuli could be selectively filtered by a common physical property (Broadbent 1958). Much of the attention literature in the

1960s and 70s consisted of demonstrations of phenomena that could not be handled by filter theory, exemplified by the famous cocktail party where hearing one's own name in an unattended conversation argues for semantic processing of "unselected" inputs. Those who believed that all inputs are fully analyzed before any selective mechanism becomes operative were called late selection theorists (Deutsch & Deutsch 1963, Norman 1968). Broadbent, and like minded early selection theorists, modified their positions to a relative suppression of unattended inputs and raised some difficulties for late selection theories (Broadbent 1970, Treisman 1964). Late selection theories do not explain why unattended events do not provide a contextual bias (unless they "breakthrough" into consciousness, like the name at the cocktail party), why alternate items presented to eye and ear must be sorted by modality rather than time of input, why practiced reduction in distractor interference is reversed by changing the features of distractors, and why false alarms rise with breakthroughs.

Late selection theorists demonstrated paradigms where concurrent tasks do not seem to interfere, if sensory and motor competition are avoided (for example; playing musical scores or typing written material while repeating heard speech). Early selection theorists claimed that careful examination of the data would show changes with the addition of a concurrent task, and explained the small size of the effects through the automatization of highly practiced redundant tasks.

Broadbent (1970) proposed dividing attentional mechanisms into those that selected a feature of the stimulus (stimulus set), and those that selected by appropriateness of an associated response (response set). For example, report of numbers in an array of letters and numbers was thought to use response set, since the letters were not associated with any

elements in the allowable response vocabulary. Report of only red numbers in an array of red and black numbers was thought to use stimulus set, since color could be used to select stimuli, (and distractors were associated with allowable responses). It was shown that paradigms using stimulus set would support early filter schemes, while use of response set would support late selection. Some subsequent discussants have used the two types of set to argue for the two theoretical positions. However, Broadbent's point was that while the two mechanisms had different properties, both had been demonstrated in attention experiments. This infers that both early and late selection mechanisms exist.

Basal arousal level must determine the range of processing that takes place in any given context. Within this range, the depth of processing of individual events is a function of two types of factors. First, every perceptual array must have a pre-existing memory "node" strength (Anderson 1983) that is a function of long-standing predispositions. This corresponds to the general ease of activation of a learned cell-assembly. Secondly, selective attention allows temporary biases to increase the tendency to perceive certain events; the central support for selective assemblies proposed by Hebb. The second factor probably embraces multiple mechanisms. Certainly, one works by actively attenuating the further processing of unselected events. Unattenuated events are processed as far as basal arousal and node strength allows. Rejected events with high longstanding node strengths, such as our names, may reach semantic levels of processing earlier, or otherwise overshadow weaker events in "attended" channels.

In the Broadbent (1970) visual experiments, if the array of letters and numbers is presented under instructions to count the letters, the

results are unlikely to change. Yet the distractors are now just as associated with an acceptable response as the targets (Increment an internal count by one for each event). It is only the rules for applying the response that allow selection. These rules always involve information derived from processing various features and codes of the stimuli. It was this line of thinking that must have led early selection theorists to pay more attention to the features of distractors. Categorizing was a strategy that was proposed to select by processing only those features of events that discriminate between targets and distractors (Broadbent 1982). For example; if looking for "E" in a field including O, S and C, the presence of a straight line would release response production, and attenuation of further processing would occur. With practice, the RT cost of distractors would lessen. However, if targets are inserted in a new field of W, J, I, and N, cost increases. Again, practice reduces it as a new discrimination strategy is learned, perhaps attending to a horizontal line in this case. Adding distractors with horizontal lines may again increase interference, providing clues to what specific strategies are being employed.

A more intuitive discrimination between the types of processing invoked by stimulus and response sets involves the concepts of parallel and serial processing. If the information needed for selection can be processed in parallel, there would be minimal interference between items in an array. This is relatively automatic, effortless processing. If needed information can only be obtained by a serial process, examining each stimulus in turn, little benefit would be obtained by a pre-cue. Whether processing operated on a fresh icon, or a slightly decayed one, each item would need the same deep analysis before attenuation of further processing would be safe. With

effortless parallel processes, the decay level of the icon can become a major determinant of behavior.

If the characteristics defining the attended stimuli are analyzed in parallel, then stimulus set operates by attenuating analysis of unattended stimuli. If the attended characteristics must be analyzed serially, a response set mode is more useful. Although Broadbent defined response set in terms of attention to a category where the unattended stimuli had no associated member of the "response vocabulary", the operative distinction may have been whether processing could proceed in parallel. If asked to count the number of letters, I would expect the same pattern of results as when asking for report of letter names.

A recent paper argues convincingly for dividing the different theories of attention into those that believe attention operates on perceptual processes, and those that place attention outside of this domain (Johnston & Dark 1982). If perceptual processing is conceptualized as activation of memory nodes by occurrence of a stimulus, it may include processing at semantic levels. This processing is effortless, rapid, and not necessarily available to consciousness. These are the characteristics of automatic processing (Schiffrin & Schneider 1977). However, intraperceptual theories hold that this process can be influenced by set to (still automatically, according to a rigidly preset program) use featural feedback to influence the amount of perceptual processing. After the activation of nodes by a stimulus, extraperceptual processing comprises the flexible, deliberate actions of a central executive. Extraperceptual theories agree that the central executive can support some nodes over others, but only after the automatic bottom-up spread of activation by an external event has run its course. Intraperceptual theories feel top-down processes interact with

bottom-up perception such that perceptual processing of attended events is increased, unattended events decreased, or both. This is obviously a restatement of the early vs. late selection controversy. However, it uses useful terminology for placing the controversy within a larger theoretical framework.

Johnston and Dark (1982) find that much of the evidence for semantic processing of unattended events is attributable to the well established semantic priming effect whereby presentation of a prior word facilitates the processing of associated later items. While the priming effect has demonstrated semantic level processing of unattended stimuli, it is generally accepted as being automatic and perceptual in locus (Shiffrin & Schneider 1977). Many arguments of extraperceptual theorists rest on the questionable assumption that unattended stimuli cannot be suppressed when semantic level processing can be demonstrated. Johnson and Dark (1982) attempt to clarify the meaning of these studies by developing a measure for relative depth of processing of attended and unattended stimuli.

While participants listened to dichotic lists in order to repeat items in a target category, occasional ambiguous words were projected onto a screen. This was a signal to free associate one word, and then return to the primary task. Before and after some visual presentations, pairs of words relating to one of the two meanings of the ambiguous word were presented to one ear. This ear could be the attended or unattended ear under focused attention instructions (repeat members of the target category only in a given ear). It could also be an attended ear under divided attention instructions. The extent to which the auditory word pairs disambiguated the visual word, (relative to the divided attention results), was taken as a measure of their depth of processing. Items in the rejected ear had no

disambiguating impact on free-association responses to visual words. Results demonstrated greater semantic priming in the attended focused ear, and suppressed priming in the rejected focused ear, relative to the baseline condition. In other words, the strongest form of intraperceptual theory was supported; where perceptual processing is enhanced in attended channels and suppressed in unattended channels. If extraperceptual theorists do not accept these results as a proper index of perceptual processing, they must propose a less disputable index, or face the charge that extraperceptual theories cannot be falsified.

However, Hoffman and MacMillan (1985) reject the supposition that semantic priming is purely perceptual. Since these effects are vulnerable to disruption, or even reversal, by a concurrent task, they feel that a controlled processing component is indicated. The data is also consistent with a concept of processing that proceeds in parallel up to some resource limit where it derails to serial operation, as when my two hands can perform separate tasks up to a level of complexity that requires sequential operations.

An analysis of the conditions under which semantic priming can produce RT cost on subsequent decisions (negative priming) has been reported by Allport and associates (1985). Ignored distractors only slowed down identification of associated items presented subsequently under three conditions. Distractors must be "selected against" such that; 1) the distractor cannot be reported while, 2) the concurrently presented target can be reported, and 3) the subsequent probe word demonstrating increased RT must also be selected from a concurrent distractor. Violation of conditions 2 or 3 result in positive rather than negative priming. In other words, if the attended stimulus presented with the distractor cannot be

reported, or if the following test word (which is associated with the prior distractor) is presented alone for identification, the RT will be faster than that obtained with a neutral distractor preceding the test word. If the first condition is violated, selective performance appears to disintegrate.

The authors use a clever experiment to strengthen the extra-perceptual view that the absence of interference or facilitation applied to concurrently presented items does not prove the absence of higher level processing of those items. Obviously, there must be a measure of this processing somewhere if they are to be convincing. They use the negative priming effect on subsequent items. They reason that if attentional filtering is made very easy, (by presenting the attended item at fixation with the to-be-ignored distractor elsewhere), the purported suppression of unattended inputs should be greater, and thus negative priming less, than when the location of target and distractor could not be predicted. Concurrent priming of distractors is shown to be nil, while negative priming of subsequent targets is greater in the easy condition. I have two concerns about this data. Firstly, the other experiments use red targets and green distractors. This experiment uses the reverse. There are reasons to believe that red may be a more difficult color to ignore. Combined with the convincing demonstration made elsewhere in the same paper that the distractor must be successfully selected against, it is possible that the difficult condition has caused a breakdown of suppression. If only a small number of trials showed facilitation instead of suppression, the larger negative priming in the easy selection condition would not be surprising. The second concern is that in most of the other experiments, Allport et al. use a catch trial to make sure that the distractors can not be reported.

Subjects able to report distractors are dropped from analysis. It is unfortunate that no catch trial is reported with the red distractor.

Although I am not totally convinced by the experiment above, Allport et al. make two very intriguing observations. Firstly, they point out that the superiority of stimulus set selection may derive only from those attributes whose neural representation takes the form of a spatiotopic map. It should not be surprising that these codes are able to cue attention to a location qualitatively better than attributes like semantic association which are thought to have a more diffuse neural representation. If stimulus-set is a function of anatomic structure, its ease is a less convincing argument against concurrent automatic bottom-up processing.

The second point involves the proper way to conceptualize negative priming effects. If one reasons that the conjunction of stimulus features is the operation needed to operate selectively (like color and name codes in Allport et al.), the results may be explained by retroactive interference rather than active inhibition. Items are presumed to have completed linkage of attribute codes when they reach consciousness (identity can be reported). In terms of cell assembly theory, perception of a red X means the assembly representing the color red is activated along with the assembly representing the name "X". If selection is postperceptual, then report of target is likely to mean that distractor processing has also succeeded in attribute linkage. When a previous distractor appears subsequently linked to an attribute that makes it a target, the old linkage must be broken before a new one is formed, and this operation may account for the RT increase. For example, assume one is asked to report red letters and ignore green distractors. If a green X is presented with a red Z, and then a red X is presented with some other green distractor, RT to name the second target

will be higher than if a neutral Y distractor had preceded it. This view holds that target readout requires linkage of X with red, and since it was recently linked to an incompatible color, the green-X linkage must first be broken. If neither of the first pair is reported, linkage is assumed to be incomplete. Therefore, instead of interference, only the facilitation of the activated but unlinked X will develop. If linkage is not needed to readout the second target, as when there is only one item presented, there is also no need to break the previous color-letter linkage, so facilitation develops.

This framework deserves serious consideration. By emphasizing structural constraints and strategies of extraperceptual information processing, it provides better parsimony than most late-selection approaches. This crosscode interference view predicts negative priming for sequential single presentations, if they must select by crosscode linkages. However, interstimulus interval may be important in terms of decay of incompatible bonds (Hoffman & MacMillan 1985). In this scheme, active inhibition must also work on conjunctions of features rather than isolated codes.

One further point should be made concerning the locus of attention issue. The additional data gleaned from this stimulating controversy, and the resulting qualifications of the two camps of theorists render it closer and closer to a non-issue, in the way that the importance of hereditary and environmental factors in control of behavior has become a non-issue. The only sensible answer to the latter question is that both factors are important and must be considered in any general explanation of behavior. The majority of attention theorists would agree that there is a degree to which environmental stimuli activate cognitive units regardless of set, and further operations dependent on set. Any explanation of attention must

primarily be concerned with the latter. But whether one places the beginning of attention within the realm of perceptual processing, or outside of it becomes less important than characterizing the processes and strategies used in selection. In other words, let us suppose that the strongest form of intraperceptual theory is correct. Attention can attenuate the processing of some channels and increase the processing of others. Compared to a neutral state, there will be a limit on the degree of suppression that can be achieved. One might define perceptual processing as that degree of processing that just reaches the level at which suppression can begin, and call attention extraperceptual. On the other hand, one could define the neutral baseline as normal perceptual processing, and find that attention is intraperceptual. Since there is no way to register a stimulus array without any passive or active attentional processing, (some passive biases are surely hard-wired, and prior experience can translate into preference), the proper baseline measure of purely perceptual processing can always be disputed. It is far more useful to uncover relationships between tasks and stimuli, as in the discovery of the conditions determining the valence of semantic priming. Whatever theory motivates these discoveries, they move us toward a better understanding of the mechanisms of attention.

Endogenous ERP Components: Contingent Negative Variation

ERPs influenced by internal set are superimposed on the pattern of stimulus-bound or exogenous deflections. For example, a series of unattended tones will elicit a number of waves including a negative deflection at about 100 msec post stimulus (N1), followed by a positive deflection at about 180 msec (P2), followed by a return to baseline. If the

tone eliciting the N1-P2 complex is a cue that an important event will take place in a preset interval, the N1-P2 complex will be followed (about 200 msec later) by a slow negative deflection known as the contingent negative variation (CNV). The CNV refers to the slow negative potential shift that develops between a cue which precedes presentation of a stimulus to which a motoric or mental response must be made, and the occurrence of the relevant stimulus (Walter 1964, Loveless 1979, Picton and Stuss 1980 and, for a novel interpretation, Rockstroh et al. 1981). CNV amplitude increases with greater probability that the relevant stimulus (S2 where the cue is designated S1) will occur (Rockstroh et al. 1981), and with motivational variables (greater amount of reward associated with response to S2). It decreases with unexpected processing demands between S1 and S2 (Teece et al. 1984).

Mapping studies show that the CNV is bilaterally symmetrical, although contralateral motor components may be superimposed (Syndulko & Lindsley 1977). Hillyard (1973) showed that bilateral amplitudes persist even when a split brain patient is cued on only one side. Further evidence for a subcortical mechanism came from studies of focal lesions, where CNV was only attenuated directly over the damaged zone (McCallum & Cummins 1973). It has been proposed that CNV results from mesencephalic reticular formation neuromodulation of cortex (Desmedt & Debecker 1979, Skinner & Yingling 1977).

CNV amplitude appears to adapt to paradigmatic changes. Subjects show high CNV phasic alertness when diurnal rhythms showed the lowest tonic alertness (Posner 1978, chapter 5). CNV has been reported to increase when responses demands were increased, although this relationship may be altered by interactions with other variables. If distracting sounds are

introduced only at random trials, a supernormal CNV will develop on trials where no distractor is presented.

If the S1-S2 interval (interstimulus interval) is greater than three seconds, two components of CNV can be reliably distinguished. The early component begins about 400 msec after S1 and lasts about 1500 msec, by which time it may have rejoined the pre-S1 baseline, and will certainly have passed peak amplitudes. The scalp distribution of early CNV shows maximum amplitudes over fronto-central cortex. It is affected by S1 parameters and attenuates quickly with repeated trials. Ritter et al. (1980) used all combinations of auditory and visual S1 and S2. Early CNV showed a scalp distribution that was maximal over association cortex of the modality used by S1, and was unrelated to S2. Late CNV showed a non-significant tendency to be distributed more posteriorly with a visual S2. Early CNV is generally associated with the orienting responses (OR) that follow a signal.

The late component is potentially of longer duration, depending on interstimulus interval. It develops slowly and peaks with delivery of S2. It is more posteriorly distributed, and is not affected by S1 parameters. It is sensitive to S2 relevance, probability, and associated task demands. It attenuates more slowly than early CNV with repeated presentations. In most experiments, late CNV has been associated with motor preparation. However, it has been demonstrated when no motoric response is required and has been differentiated in hemispheric distribution from the known complex of response related potentials (Kutas 1984). Teece and associates (1984, p.283) showed that motor acts occurring between S1 and S2 caused increases in EMG, heart rate and reaction time, while late CNV decreased in amplitude. The same dissociation was found for the supernormal CNV on trials when a distractor might have been presented, but wasn't (Teece et al.

1984, p.289). This presents difficulties for the motor reductionist view of late CNV, but is consistent with explanations featuring the concept of attention.

Ruchkin and associates (1986) recently recorded late CNV in a paradigm where subjects initiated trials by predicting whether the two events that followed would be the same or different (each event could be a flash, or a flash accompanied by sound). CNV amplitude was largest at the presentation of S2, and showed a scalp distribution more posterior than early CNV or the motor preparation component. Moreover, in some conditions motoric responses were delayed (2-4 sec after S2), and in others there was no motor response. Late CNV amplitude was decreased when S2 delivered no information. The authors conclude that their late CNV relates to the informational properties of the stimulus it anticipates.

If there is anticipation of random shocks occurring at any time during the interstimulus interval, there is no separation between early CNV and late CNV. If a later block of trials will control escape from painful shocks, CNV amplitude will increase over trials, instead of attenuating. If previously established control over an aversive S2 is suddenly lost, a large post imperative negative variation (PINV) will occur after S2, (as opposed to the usual return to baseline or positive component). If important and unimportant S1s can be differentiated, only important S1s will be followed by CNV.

Endogenous ERP Components: Late Positive Component

The complex of late positive components has most often been described as P300; a centroparietal scalp-positive potential that increases in amplitude with the meaningfulness and rareness of attended stimuli.

When two channels of information, such as ears, are designated by instructions to be attended and ignored, P300 is small or absent to rare stimuli in the ignored channel. However, the instructions are effective in reducing P300 amplitude only when other tasks exist to focus attention, calling into question the ability to prevent processing of stimuli under some conditions. When only one channel of stimulus-differentiation exists, (for example: respond to all right ear stimuli), P300 is generally earlier and of larger amplitude (Wilkinson & Lee 1972, Desmedt et al. 1977). Characterization of P300 as a sign of resource-limited processing is supported by finding decreased P300 amplitude to a probe stimulus when the primary task is increased in difficulty (Wickens et al. 1984). The importance of the automatic/controlled processing dimension is indicated by the attenuation of this effect with practice.

Similar components have been labelled as P300 in auditory, visual and somatosensory stimulation modalities, with visual P300s having the greatest amplitudes and latencies (Snyder et al. 1980). While it has been suggested that visual stimulation is inherently less arousing than the other modalities, it is also likely to be more consciously processed, (perhaps as an adaptive response to getting less automatic processing), thereby being associated with a differential course of development. It would be interesting to measure the modality-specific characteristics of P300 in the very young.

A dizzying array of constructs have been proposed as representing the functional significance of P300. As previously mentioned, Hillyard and associates (1973) identified it with Broadbent's response-set. Other ideas have included orienting (Ritter et al. 1968), relaxation from an aroused state (Karlin 1970), information delivery (Peters et al. 1977), information

use (Johnson & Donchin 1978), equivocation (Ruchkin & Sutton 1978), template-matching (Thatcher 1977), memory (Sanquist et al. 1980), consciousness (Posner 1978), and an all-purpose general processor. Unfortunately these concepts have seldom been operationalized and are either too nebulous to be testable or have not been consistent with data collected under designs developed by other laboratories. Like blind men feeling different parts of an elephant, each theorist finds support for a cherished notion, and finds fault with the others.

Attempts to understand P300 have recruited special subject populations. Hyperactive children have shown reduced P300 amplitudes in attentionally demanding situations, and normalization with methylphenidate (Klorman et al. 1979, Loisel et al. 1980). Reading retarded boys were also found to have aberrant P300s, although in contrast to hyperactives, they were not impaired on behavioral measures of attention. Lovich and Stamm (1983) concluded selective attention was intact, and therefore P300 must index some later processing. On the other hand, Musso and Harter (1978) found normal IQ reading/perceptual learning disabled children showed larger amplitude P300s, although behavioral measures were undifferentiated from controls. They interpreted this as more effortful processing to reach the same degree of performance.

Schizophrenics have shown aberrant P300s, but the attempt to differentiate disturbances of late versus early evoked potential components are not convincing (Baribeau-Braun 1983). Rather than comparing schizophrenic performance with normal controls, it would be more interesting to equate evoked potential response in either early or late components with other impaired groups in order to show a dissociative effect.

For example, a number of studies have examined P300 in the aged (Ford, Duncan-Johnson et al. 1982; Ford, Pfefferbaum et al. 1982). Latency of P300 increases with age, and the P300-reaction time correlation decreases. Especially in the elderly, P300 may be generated after the initiation of a response. Stressing speed of response over accuracy decreases P300 latencies and generally decreases the P300-reaction time correlation.

Squires and associates (1975) resolved much confusion when they showed that what had been labeled P300 was actually a complex of distinct components. They discussed an early P300a distributed more frontally and related to the orienting response, a more posterior P300b that represented the component most P300 studies were addressing, and a superimposed slow wave, which was posteriorly positive but of negative polarity in the frontal region.

Friedman and associates (1978) showed a further response-related complex by time-locking the evoked potential record to the EMG burst preceding motoric response. They also demonstrated that the various components could be separated better as the reaction time lengthened for both stimulus-bound and response-bound records.

When demonstration of P300 following motor response initiation invalidated early suggestions relating it to discrimination, attention shifted to the earlier negative deflection (N2) at about 200 msec, which was highly correlated with P300 and RT (Ritter et al. 1979). However, N2 generally appeared to deviants regardless of channel attention. While there is a consensus that N2 has something to do with discrimination, it has been shown to be made up of separable components. Näätänen et al. (1982) propose that an exogenous modality-specific N2a records deviance up to a

variable threshold, where it triggers a fronto-central N2b. N2b registers detection of deviance as part of an endogenous triphasic P2b-N2b-P3a complex associated with the K-complex of the orienting reflex. They also consider it possible that their 2b-complex may only register involuntary attention to deviance, as when sleepy subjects show huge K-complexes when wandering attention is recalled by an event. The problem lies in showing where the involuntary shifts in attention occur. Although instructions to not attend, yet respond, are somewhat contradictory, I find subjects could estimate how many unattended deviants broke into their attentional stream during a run. Asking for button press to these unwelcome intrusions might help to choose between the alternatives of Näätänen et al. (1982). In their current scheme, P3b is an artefactual product of other components.

Fitzgerald and Picton (1983) showed a frontal N2b in the ERP produced by standards mistakenly classed as deviants, supporting its endogenous nature. It was also enhanced by difficulty of discrimination, causing them to associate it with effort allocated to mismatching stimuli, rather than detection of mismatch. In their model, N1 and N2a reflect exogenous template matching. Attention (along with other factors) controls the threshold needed to elicit N2b, which indexes effort allocated to classification and triggers the third stage of higher order control processes. These processes produce the P3s and slow wave. Functionally, they adjust the threshold for subsequent N2b elicitation and update neuronal models.

Besides the relationship of P3s with preceding N2s, all of the above reported ERP components must be accounted for in any comprehensive model of how the brain responds selectively in attentional tasks. Visual ERP phenomena analogous to P300a and P300b were reported by Harter and Guido

(1980). In addition to finding positive potentials corresponding to the two P300s in distribution and latency, this study also showed negative shifts analogous to early and late Nd. Ruchkin and associates (1980) found task related changes in "P300" that were actually due only to slow wave changes. They also found significant loading of the CNV component of a principal components analysis on the LPC, which demonstrates another potential confound when base to peak dependent variables are used. An increase of slow wave amplitude with decreasing accuracy in a signal detection paradigm was interpreted as reflecting the need for further processing.

Currently, the most widespread hypothesis of P300 is as a context upgrading mechanism that can serve as a metric of stimulus evaluation time (Ritter et al. 1972, Duncan-Johnson & Donchin 1982, Wickens et al. 1983, McCarthy & Donchin 1981). This view proposes P300b is feedback enabling a hypothesis generator to modify future hypotheses, hence it's sensitivity to perceived frequency and non-occurrence (in the case of emitted potentials). Attention is thought to enable this mechanism. The role of P300a is discussed less often. Grossberg (1980) theorizes that P300 is a reset mechanism whereby short-term memory is modified by new occurrences. Since single-trial P300b often occurs after response initiation, perhaps P300a, with it's frontal distribution and resemblance to an orienting response, is a better candidate for this function. Pritchard (1981) speculates that frontal P300 may index revision of physical models while parietal P300s may update more cognitive models. This dimension must be operationalized to test his idea.

Recent evidence that P300 may be subcortically generated has important implications for understanding the physiology of the LPC (Halgren et al. 1980). Knight (1984) reports normal P300a to surprising

sounds in both frontal and parietally damaged patients. Since there was no asymmetry over any damaged hemisphere, Knight speculates that P3a is subcortically generated, but subject to inhibition by frontal lobes. Frontal damage resulted in bilateral loss of habituation to the surprise sound.

These data lend support to the challenging theory of Skinner and Yingling (1977) on neural mechanisms of attention. This theory proposes that the extensive connectivity between the prefrontal cortex, thalamic reticular nucleus and mesencephalic reticular formation serves to modulate attention to serial events. P300 is seen as frontal inhibition of diffuse MRF neuromodulation of cortex. This MRF-generated negativity results in CNV and other slow negative potentials. A correlation was demonstrated between stress-induced slow negativity and the cyclic adenosine monophosphate (cAMP) content of tissue adjacent to the recording electrode in rats. Stimulation of MRF produces bilateral CNV-like negativity in cats. Lesions of preoptic basal forebrain areas in man disturb OR habituation, presumably by disinhibiting MRF arousal.

Since P300 can occur after a differential motor response, it must be a post-decision event. If the relevant mechanism is disinhibition of subcortical arousal systems by frontal cortex, what is the significance of P300? It cannot be the mechanism of habituation, since non-targets also show habituation. Friedman and associates (1975) showed that the largest P300 amplitude to the words of a sentence will be found to the last word, regardless of where in the sentence task-relevant information is found. Desmedt and Debecker (1979) feel that this indicates P300 represents a post-decision cognitive closure mechanism that clears the processing capacity for upcoming items. When they made the interstimulus interval regular, P300 amplitude almost doubled, supporting a closure or reset

mechanism reflecting the additional focusing of attention enabled by predictable stimulus onset, and reflected in CNV. The correlation between CNV and P300 amplitude was .75 (Desmedt & Debecker₂ 1979). They also demonstrate P300 without CNV (using near-threshold stimuli and variable interstimulus interval) and argue that attention presumes a DC negativity, which infers that resolution of negativity will correlate with factors other than CNV (Desmedt & Debecker 1979).

This formulation bears some resemblance to other proposals that P300 functions as a reset, or relaxation-from-arousal mechanism (Grossberg 1980, Karlin 1970). But it retains a flexibility that avoids the pitfalls of these other views. It is not short-term memory which is reset, but the resources that were committed to processing the stimulus. It can correlate or not with CNV depending on paradigmatic variables. Does this make it untestable? Bauer and Nirnberger (1981) used 25 μ volt baseline shifts (over 2 seconds) to trigger presentation of slides designed to teach a concept. Subjects triggered by negative DC-shifts learned faster, and had 25% larger P300 than those triggered by positive shifts. A relationship with baseline negativity independent of CNV is inferred. While these results are preliminary, they show that this view of P300 can generate significant research, as well as accommodating a wide range of sometimes puzzling findings. Largest P300s to final words of sentences supports a chunking-type of operation that can be withheld, at least for a while, like breathing. The large P300 may wait until a propitious moment. After occurrence of a target stimulus, probability of another important event is usually lower. More important, there is a shiny new internal representation of the attended event. It is easy to see how this could ease attentional needs for a short time (Näätänen 1982).

Deecke and associates (Deecke, Bashore et al. 1984; Deecke, Helse, et al. 1984) take the concept of a relaxation/reset P300 one step farther. They interpret the known series of movement related potentials as indicating increased cortical negativity when a brain center becomes active, followed by cortical positivity (which they term a relaxation potential) as firing in that area subsides. Deecke and associates report a unilateral negative potential that represents attention to one hemifield, and show how operant changes that require clearing in order to meet subsequent demands generate relaxation positivities. They finally conclude that P300 is a cognitive analog to a relaxation positivity, resolving the steady accumulation of DC negative shift since the last clearing procedure. Because the development of cortical negativity is mostly very gradual, it is not picked up using the filters and timescale used to show the fast P300 resolution. Under this scheme, motivational variables are important to P300 because they affect arousal and preparatory negativity. Uncertainty enables and quantifies the build-up, and temporal mechanisms track its progress to provide for homeostatic feedback.

Along these lines, Fitzgerald and Picton (1984) used .5, 1 and 2 sec interstimulus intervals with target probability held equal. They conclude that temporal probability is a more important determinant of P300 amplitude than sequential probability. This finding also supports a homeostatic cognitive closure mechanism better than a context upgrading mechanism. A mechanism that releases built-up negativity also makes sense of the positive correlation between amplitude and latency across modalities (Wood et al. 1984). Later relaxation would infer a greater total negativity has been built-up.

A Model of Selective Attention

My view of perception is essentially Hebbian and I borrow strongly from the theories of Skinner and Yingling (1977) and Näätänen (1982) in my attempts to understand attention. The data reviewed above is inconsistent with parallel processing of all ERP components (there are dependencies such as N2-P3), strict serial processing, (endogenous components can overlap as with N_A and N2), or a model where each component starts at a fixed time. Some cascade scheme, where a certain amount of processing in a prior stage tends to initiate subsequent stages is more likely.

In order to best separate the different event related components concerned with selective attention, long intertrial intervals and cued oddball paradigms can be recommended. Figure 16 summarizes components expected when an auditory target is presented in such a paradigm (see figure 16, Appendix B). Understanding the functional interrelationships between these phenomena requires a general understanding of how the human brain processes afferent signals.

All incoming signals have an arousing function as well as a cuing function. This arousal is mediated by the reticular formation (RF) of the hindbrain, through interaction with the thalamus. This results in excitation of frontal cortex and subsequent excitation of selected cortical areas. RF stimulation produces slow cortical negativity and mammals show such negativity spontaneously during exploratory behavior, alerting and awakening (summarized in Desmedt & Debecker 1979). Slow positivities are recorded during sleep onset, reduction in alertness, satiation and grooming. These effects are believed to be produced by RF neuromodulation of cortical excitability (Skinner & Yingling 1979).

Human frontal lobes illustrate well the adage that ontogeny recapitulates phylogeny. They are the most recent evolutionary change in primate brain and the last part of the brain to be myelinated. Moreover, they have the richest system of corticofugal connections to RF, thalamus and hypothalamus, and the most extensive network of direct connections to all important cortical areas. They receive information from all sensory modalities.

Any human activity results in synchronization of electrical activity at many points in cortex. The first evidence of this synchronization is always seen at frontal sites (Livanov et al. reported in Luria 1980 p.285). Since schizophrenia is marked by distractability (a breakdown of normal attentional selectivity), it is interesting that this synchronization is increased in schizophrenics and is normalized by neuroleptics (Livanov et al. reported in Luria 1980 p.285).

The frontal lobe may be separated into a dorsolateral and a mediobasal division. While damage to dorsolateral areas tends to disturb smooth motor functions, speech and intellectual activity, lesions in the mediobasal region are associated with state changes and disturbance of orienting responses, particularly through hyperactivity resulting from lack of habituation (Luria 1980). The return of infantile reflexes (normally seen before frontal myelination is completed) and previously extinguished classical and operant responses have also been noted. Luria (1980) concludes that the frontal lobes function to produce preliminary integration of all sensory information, the attachment of significance, creation of complex programs of goal-directed behavior, and monitoring of feedback to track the progress of these plans. More specifically, the mediobasal

division is thought to regulate long and short term global and selective activation processes that enable functional brain neural systems.

Pribram and associates have come to similar conclusions from the consideration of frontal lobe damage in humans and monkeys. A loss of purposefulness and correction of behavior, increased motor tone, and the inability to delay a response or learn new choice behaviors was noted (Pribram 1959, 1961; Pribram & Mishkin 1955; Pribram & Luria 1973). Without frontal activity, traces of associations are seen as transient and vulnerable to distraction such that intention never develops. Frontal monkeys were believed to have a loss of cortical control over core brain arousal systems leading to a failure to update neuronal models (Pribram & McGuinness 1975).

Walsh (cited in Lizak 1983) further differentiates between damage to more medial, presumably dorsal, parts of mediobasal frontal cortex, which disturbs purposeful initiation and maintenance of activity and damage to more orbitobasal sections which disturbs impulse control and the regulation of ongoing behavior. These are disorders of what neuropsychologists have called executive functions (Lizak 1983).

Frontal activity serves both to activate and inhibit other systems. Normally, when sensory information reaches frontal cortex, the arousing function of the stimulus helps activation and integration of an internal representation of the event. In the model being developed here, this represents a cognitive template which links input patterns with significance and associations. To the extent that the input pattern is not novel, the general arousing function of a stimulus is not needed for activation of this template, and frontal cortex inhibits RF excitation of itself through a thalamic feedback loop. This is the basis of habituation,

which vanishes with some types of frontal damage, and when frontal electrodes register synchrony bordering on sleep EEG patterns. In both situations, the subject will continue to reorient to a repeated stimulus. Monkey prefrontal neurons increase firing rates during delayed-response paradigms. Like CNV, this effect is attenuated by distractors (Fuster 1973). When the cat efferent path from prefrontal cortex to lower brain centers was cooled, the OR to irrelevant stimuli was disinhibited (Skinner & Yingling 1977). Clearly, frontal feedback can moderate RF arousal.

Any stimulus will also activate a sensory template, a group of cells in primary sensory cortex directly excited by receptors, and a perceptual template, a group of cells primarily in relevant association cortices which act according to temporary biases and longstanding predispositions to group sensations into percepts. It is this information which interacts with arousal in frontal lobes to produce the cognitive template which assigns significance, and plans and executes responses. Perhaps it would be better to say that the frontal lobes allow the fine tuning of this system, such that systemic energy is used to produce appropriate action most efficiently.

Let us examine how the model interprets the evoked potential correlates of selective attention in figure 16. The complex of exogenous components that follow both cue and target represent nonspecific responses to a stimulus. For example, the arousal function and activation of the sensory template require only low levels of consciousness, although they may be altered by changes in tonic state. The brainstem nuclei will passively register the presence of sound, and relay automatically processed information to thalamus. RF inhibition of the thalamic reticular nucleus will release medial thalamic areas to activate frontal cortex (Skinner & Yingling 1977). As early as the ventral cochlear nucleus (2 msec) new

sounds cause a sampling of binaural space (Hafter & Buell 1985). Direct links to auditory cortex will activate sensory and perceptual templates, including registration of localization characteristics, in the superior temporal plane (Vaughan et al. 1980).⁷ This synchronized firing and relaxation produces the N1-P2 exogenous complex, although superimposed influences may appear to dissociate the two components, just as inspiration and exhalation can be separated by task demands.

The earliest attention related component in figure 16 (see figure 16, Appendix B) is early CNV. This is interpreted here as activation of a cognitive template demanding further processing; a type of orienting. Cortical negativity is associated with the need for greater processing in many experiments (Rockstroh et al. 1982). The purpose of early CNV is to prepare the frontal "orders" that will be sent to other relevant cortical areas.

Late CNV shows these "orders" preparing relevant association areas to recognize and respond to the target, by selectively lowering firing thresholds. If this model is correct, careful experimentation should show significant modality specificity of late CNV. Although the one study extant shows only a non-significant trend in this direction (Ritter et al. 1980), it has recently been proposed that the part of late CNV which relates to the informational properties of S2 has low amplitude and is easily

⁷In the visual modality coding for spatial location is thought to produce the N1 exogenous potential from posterior parietal cortex (Hillyard et al. 1985). As reported above, single cells, as well as the N1 component appear to respond directly to spatial attention in this region. Unlike the separate characteristics of attentional modulation of auditory space, visual N1 is simply enlarged, with no morphological changes. Some authors feel this supports an earlier RF-lateral geniculate gating of visuospatial attention (Skinner & Yingling 1977).

overshadowed by other processes, such as motor preparation (Ruchkin et al. 1986). This time-locked priming of the perceptual and response templates is probably mediated by both direct neural disinhibition and indirect methods such as alterations in regional cerebral blood flow, which has shown modality-specific preparation (Roland 1981, Roland 1982).

During the first second after target presentation, a number of processes occur in parallel. The arousal level of the reticular system sets the range of cortical activity that can be elicited by specific events. This level can be increased by frontal corticofugal feedback, while cortico-cortical projections prepare posterior regions at various levels of specificity. This is how the proposed modality-specific portion of late CNV is generated. Any priming of this sort will generate increased firing in response to a wide range of events, perhaps any event in the primed modality. The resulting increase in negativity is N_A , seen in the ERP record of all relevant stimuli while the priming strategy is in use. I predict that N_A will correlate with CNV when a discrimination is expected (but not needed), and that sequential analysis will place it primarily in alternation trials of the 80%/20% run using simple RT instructions.

While N_A represents a more general arousal increase due to active allocation of attention or passive claiming of attention by "new" stimuli, there is a point at which the primed perceptual templates evaluate incoming signals more specifically. That is, if there is a specific expectation, the quite circumscribed cell groups representing these events will have lower activation thresholds than similar cells. This is the normal state of affairs. We recreate our world from microsecond to microsecond, by expecting certain stimulus configurations to occur, based on both hard-wired (automatic) and consciously effortful (controlled) processes. Expectations

can increase errors in categorization, but there is an overall savings in time to perceive and react to external events. Thus expectations are response biases, as well as lowered physiological thresholds. Early Nd is simply more firing in sensory specific association areas due to lower thresholds for expected events. High probability sequences create (probably hard-wired) expectations for the high probability event, and even if another information channel is of greater interest, Nd will show lowered thresholds for the high probability channel. It is seen in all attended channel inputs because of the trade-off between desirable target specificity and the efficiency of generating expectations for higher probability categories. When a match is recognized, there must be feedback to frontal lobes if further processing is to use controlled attentional processes. This is late Nd, representing either updating or reactivation of the frontal cognitive template for further processing.

Disconfirmation of expectations should also be a signal for further processing in organisms which hope to survive. There must be a relatively automatic mechanism to alert the system to surprises, and this leaves the N2 signature in ERPs, which is most dependent on probability but interacts with motivational variables to set operating thresholds.

At some point, the information building up in the cognitive template tracking center will disinhibit the response template. Although P300b is too late to play a part in response generation, it may be that the earlier frontal P300a may relate to decision making or response release. Frontal P300 should be carefully observed to ascertain it's relation to the response related potentials.

If late Nd is stimulus activation of a frontally based cognitive template relating stimuli to significance and plans, the difficulty in

distinguishing late Nd with short interstimulus intervals may be due to remaining excitation of this template by the preceding stimulus. That is, it may be a ceiling effect where further excitation has minimal consequences. However, conscious rehearsal may also be less important, or less effortful at short interstimulus intervals, making it difficult to differentiate between these hypotheses. The development of a maintained activation of both perceptual and cognitive templates may explain the one minute build-up period for the N1 effect, which has been shown only with short interstimulus intervals.

While more experiments have generated data relevant to P300 than any other attention-related potential, in some ways it remains the most mysterious. Within the model being developed here, if the two components of CNV index preparation of the cognitive and perceptual/response templates relevant to an expected stimulus, and the two components of Nd index match-processing at the latter and feedback reactivation of the former, with N2 detecting mismatches, the prominent parietal P300 after a rare target appears neither obvious nor necessary for selective attention.

Yet the component is reliable both within and across subjects. It's amplitude is sensitive to motivational, informational and concurrent perceptual processing demand variables. It's latency appears to index stimulus evaluation time, but can be dissociated from response processing. It's functional role must relate to processing of succeeding stimuli. Karlin (1970) suggested it represented relaxation from a state of cognitive preparedness, but this hypothesis could not accommodate the specificity and sensitivity subsequent authors have demonstrated. Grossberg (1980) believes it to be a mechanism resetting short term memory such that mismatches with expectations can be detected. However, it is difficult to

understand earlier responses from this viewpoint. Posner (1978) finds P300 to index conscious processing resources where onset indicates the selection of a signal for further processing. The incompatibility of P300-RT data with the further processing suggestion may have discouraged further consideration of the proposed relationship with consciousness. Certainly, this idea is not inconsistent with the popular notion that P300 represents the reupdating of neuronal models equivalent to hypotheses. While late Nd may represent feedback activation of a cognitive template, it may require waiting for the end of stimulus analysis before sending changes that must be incorporated into that template. However, the primary function of P300 may not be so concerned with neuronal update as with resetting the mechanism for conscious processing.

Karlin, Grossberg and the Donchin group are likely to be correct in assuming P300 to represent a reset type process, and the relationship with consciousness certainly demands consideration. But the mechanism need not be nonspecific, or a precursor of further processing on the trial where it occurs. In clinical groups with deranged P300s, perseveration is a noted symptom. There appears to be an impairment of the ability to detach attention from a stimulus that has captured it, such that responses are carried out again and again. While the current model would expect involvement of the frontally located cognitive template in preventing perseveration, the mechanism must involve other generators.

After all, lobotomized primates can still perform previously learned responses to stimuli. There must be some intact system for allocation of attention and connection of signal to plan. It is most likely a more evolutionarily primitive system in limbic structures and core brain. Damage to some of these deep structures has resulted in an inability to learn new

choice paradigms. This brings to mind the clear dissociation that has been demonstrated between procedural and declarative memory in amnesic patients (Schacter 1985, Cohen 1985). Along these lines, one neuropsychologist reports a surprisingly effective method of teaching patients with Korsakoff's syndrome through use of semantic incongruity (Mattis 1983). Similar use of semantic incongruity has generated large negative event-related potentials (Kutas & Hillyard 1980). This supports the hypothesis of two interacting systems for generating responses; one connecting directly to subcortical affect centers and the other sensitive to mismatch with neuronal models and using frontal mediation. This dichotomy has been applied to attention in the theoretical framework of Tucker (1986). Normal selective attention can be presumed to utilize both systems to focus on, and respond to relevant stimuli.

In this model, P300 is thought to be in the group which Deecke and associates (1984) call relaxation potentials (see page 78).⁸ It is primarily a subcortically initiated sign of reset of the mechanisms that allocate

⁸If we include a motor response in our model, completeness would require the addition of a whole complex of response related potentials beginning with a bilateral negative Bereitschaftspotential (BP) about 1 sec prior to movement, which gives way to a contralateral preponderance of negativity (CPN) after about .5 sec. Contralateral motor cortex generates the negative motor potential about 60 msec prior to EMG onset. After EMG, there is a negative-positive-negative-positive complex superimposed over general slow positivity. However, if the task requires cortical monitoring, positivity will be minimal until the goal is attained. In fact, each negative potential appears to be followed by a positive potential with identical distribution. The CPN is thought to result from relaxation of the less important cerebral hemisphere. The earliest BP is seen over the supplemental motor area, where the first positivity is also found. In this scheme, activation of brain centers is accompanied by increased firing which causes a scalp-negative potential. As the focus of excitation moves on, cell firing decreases, resulting in positive potentials.

attention for conscious processing of a stimulus (see Desmedt & Debecker 1979, Bauer & Nimberger 1981).

P300 signals the end, rather than the beginning, of conscious stimulus evaluation. (Automatic preset processing may continue, and be reflected in slow waves, but controlled resources are set free.) This explains its rapid refractory period, since it is itself the process of wiping the processing slate free to enhance other perceptual templates. It is responsive to the informational and motivational characteristics of the stimulus because it specifically resets only those cell-assemblies that have been "captured" by the stimulus and are currently reverberating. These recruited assemblies must be freed from repeated reverberation in order for their component cells to partake of other assemblies. It is certainly adaptive to have some mechanism to enable attention to be quickly redirected to a new environmental event. After all, the rare event that just "captured" attention may turn out to be meaningless, while a more common event shortly thereafter may reward or punish. To the extent that hard-wired systems like the orienting response can hold attention in real time, the organism is environmentally vulnerable. The most likely mechanism whereby detachment could be accomplished is a return of thalamic inhibition through the medial-thalamic-frontocortical system.

It is parsimonious to postulate that as evolution allowed consciousness more leeway to enhance different subsets of neurons, (conscious attention), a modified use of the same method of disengaging would develop. Controlled enhancement of a posterior perceptual template would result in a more posterior P300b while a stimulus that captured attention purely by hard-wired novelty might be reset by a more frontal P300a. If concurrent perceptual processing demands have allowed less

resources to be committed to a stimulus, a smaller P300 reset will result. That is, the other reset mechanisms will be time-locked to their eliciting distractors, and not the events we are averaging to. The more cells that are already part of activated cell-assemblies, the less there are to partake of ours. Reports of the extent to which a stimulus reached "awareness" may thus correlate with P300 amplitude. Perhaps eidetic imagers will have later or smaller P300s to visual stimuli. To the extent that conscious attention has been committed to lower the threshold for registering an expected percept, those resources must also be reset, resulting in an emitted P300.

The significance of the slow wave component of the LPC is unclear at this time. However, it probably consists of two associated slow waves; a frontal negative wave and a posterior positive wave. The slow wave appears to increase in amplitude with the need for further processing. Although perceptual processing is completed about the time of slow wave generation, further search for associations and meanings could be taking place in the cognitive template, consistent with frontal slow negativity, and the posterior positivity could be another of the family of relaxation potentials.

Appendix B

Figures 1-16 and Table 1

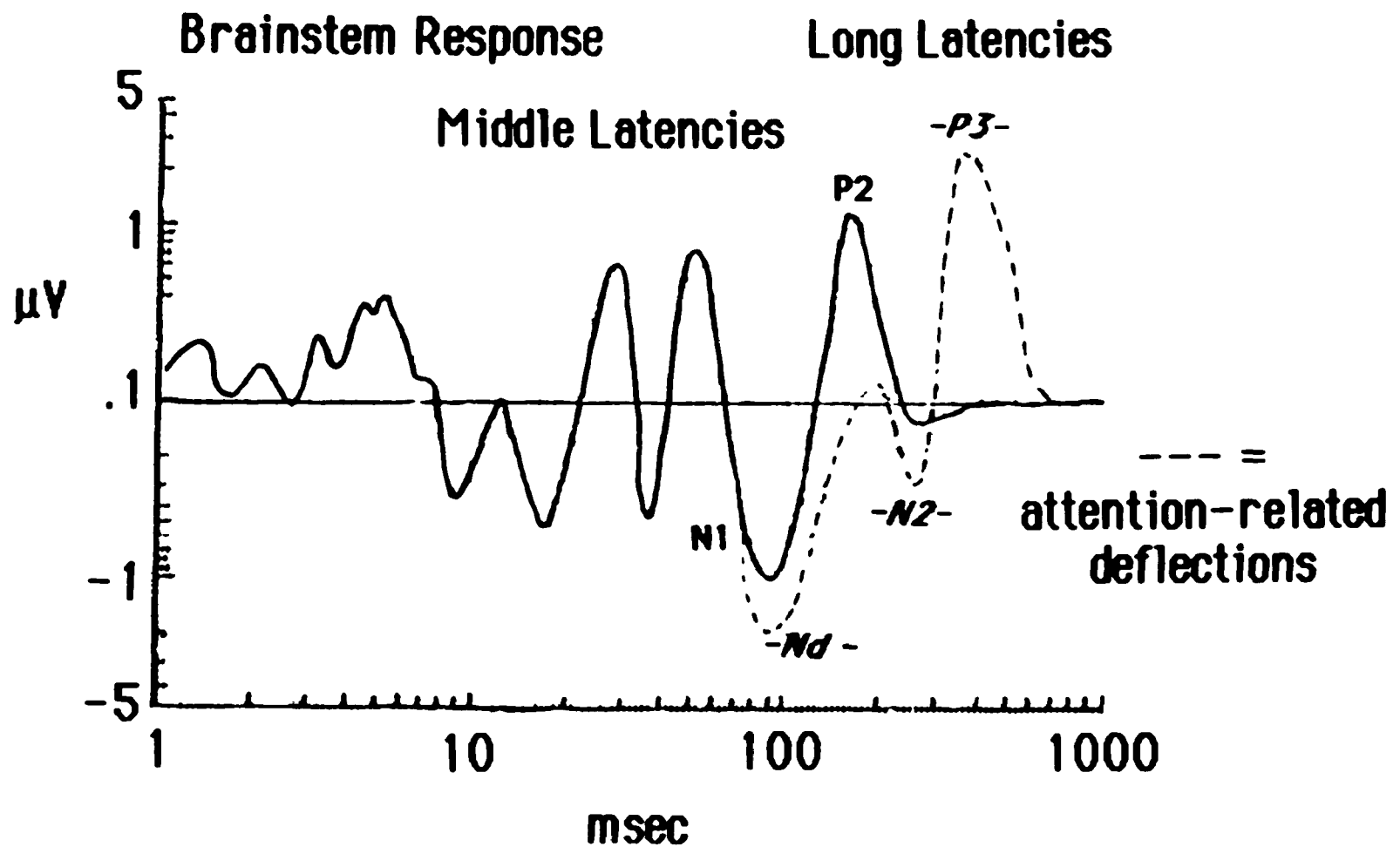


Fig 1. The human auditory event-related potential on a log scale.

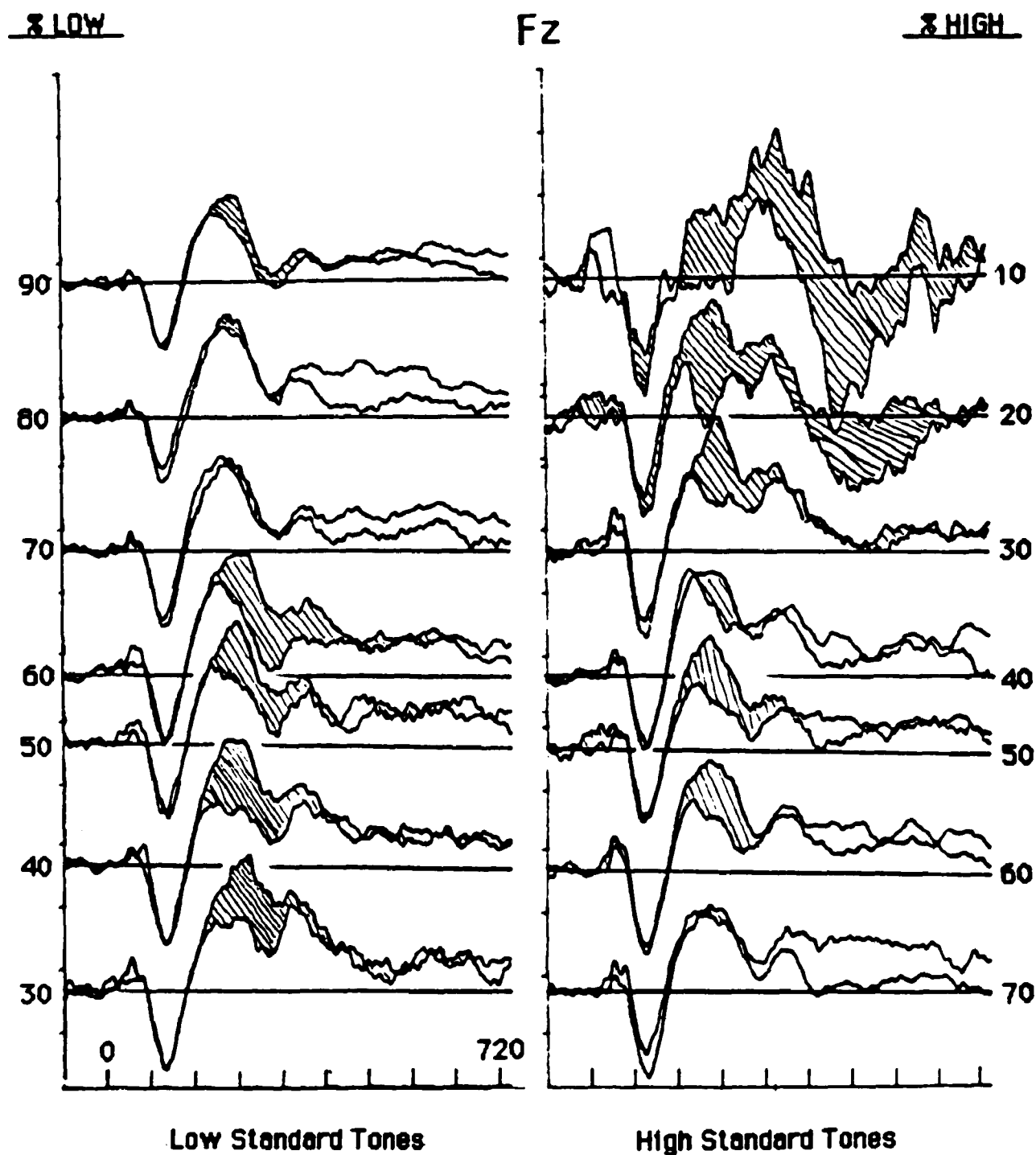
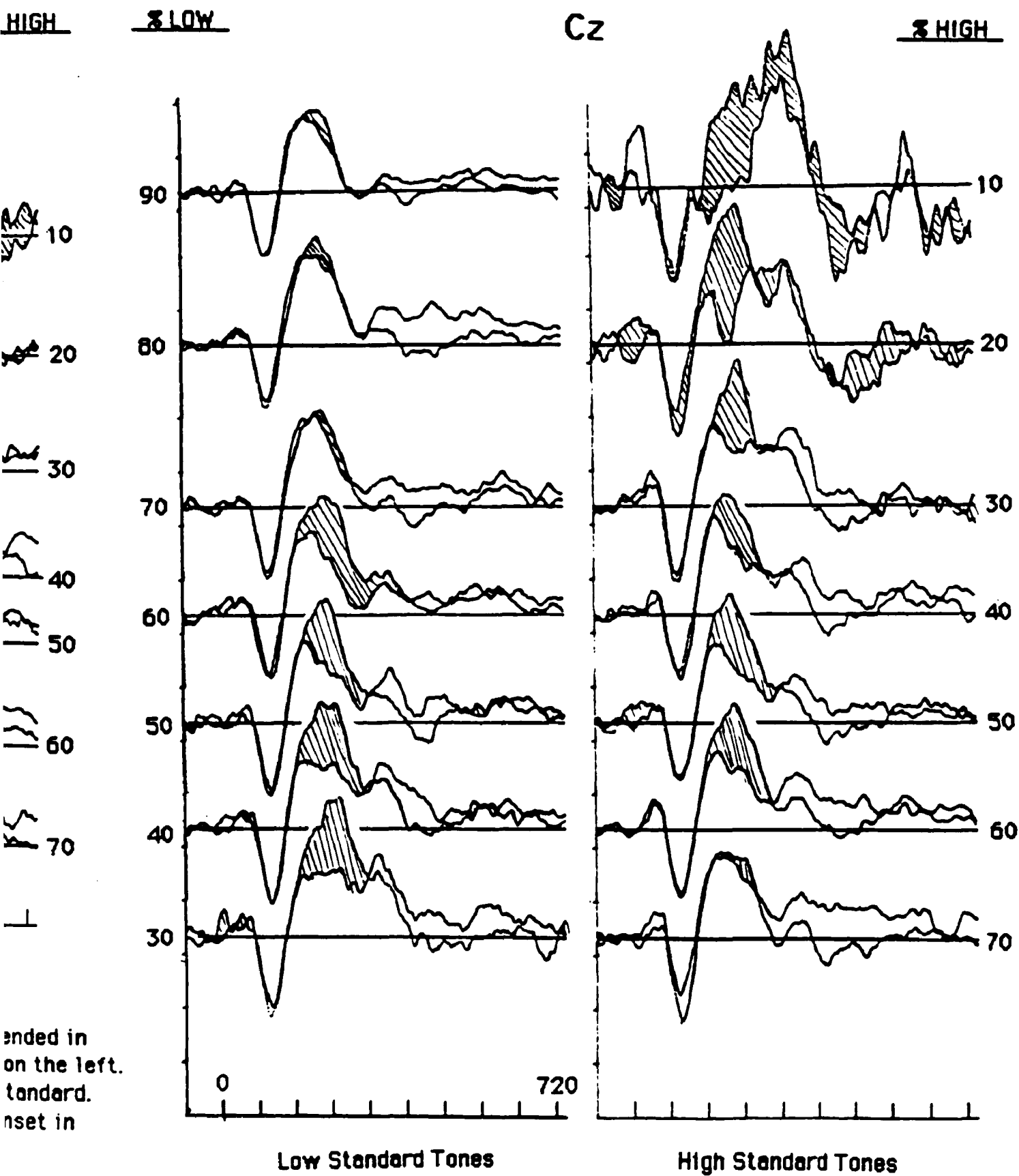
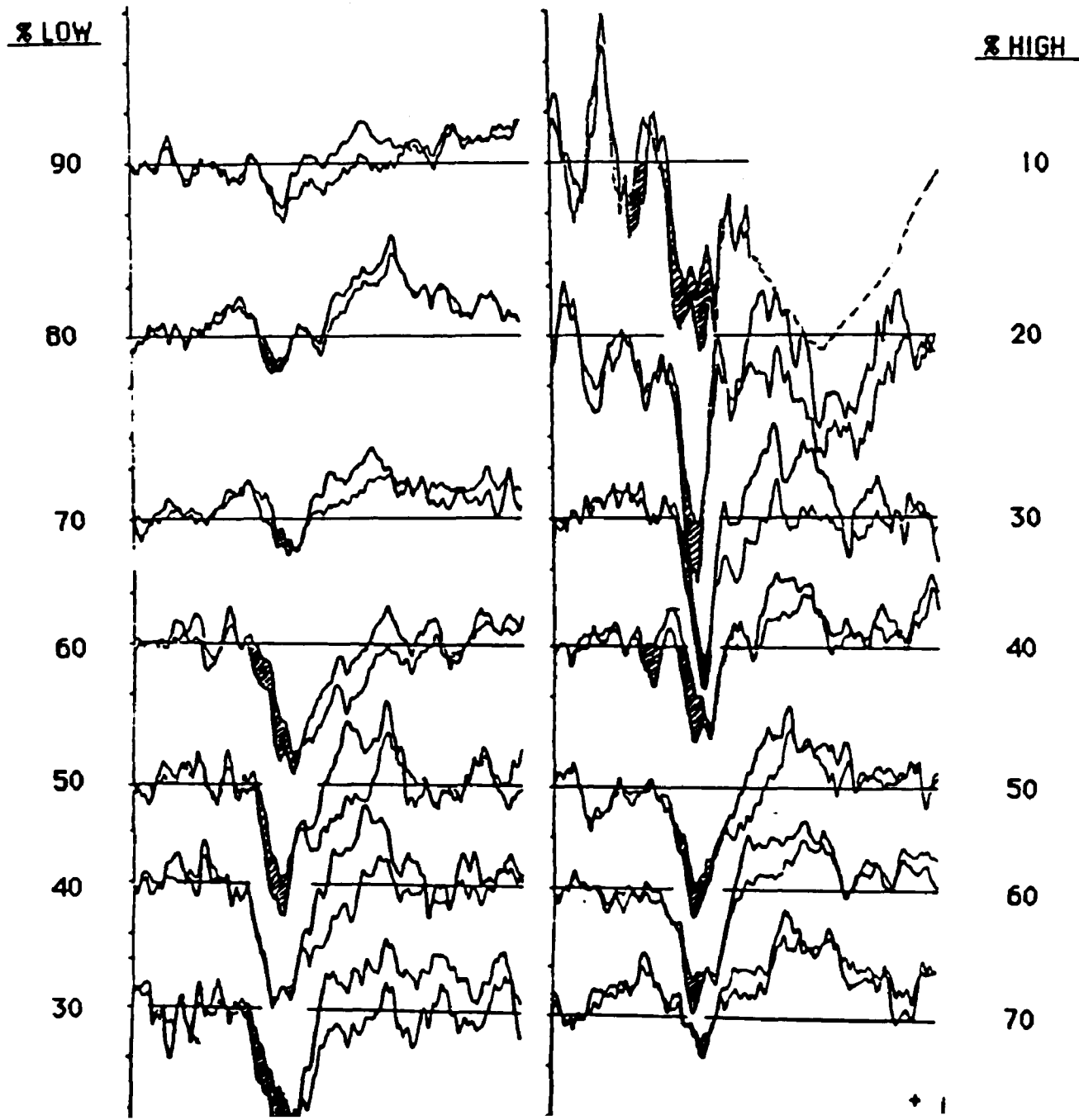


Figure 2. Grand mean ERPs for standard tones when attended and unattended in all channel probability conditions. Cz records on the right. Fz records on the left. Shaded areas show greater negativity (or less positivity) as attended standard. SCALE: 80.0 MSEC/DIV, 2.5 μ V/DIV, + = UP, '0' indicates stimulus onset in this and subsequent figures.





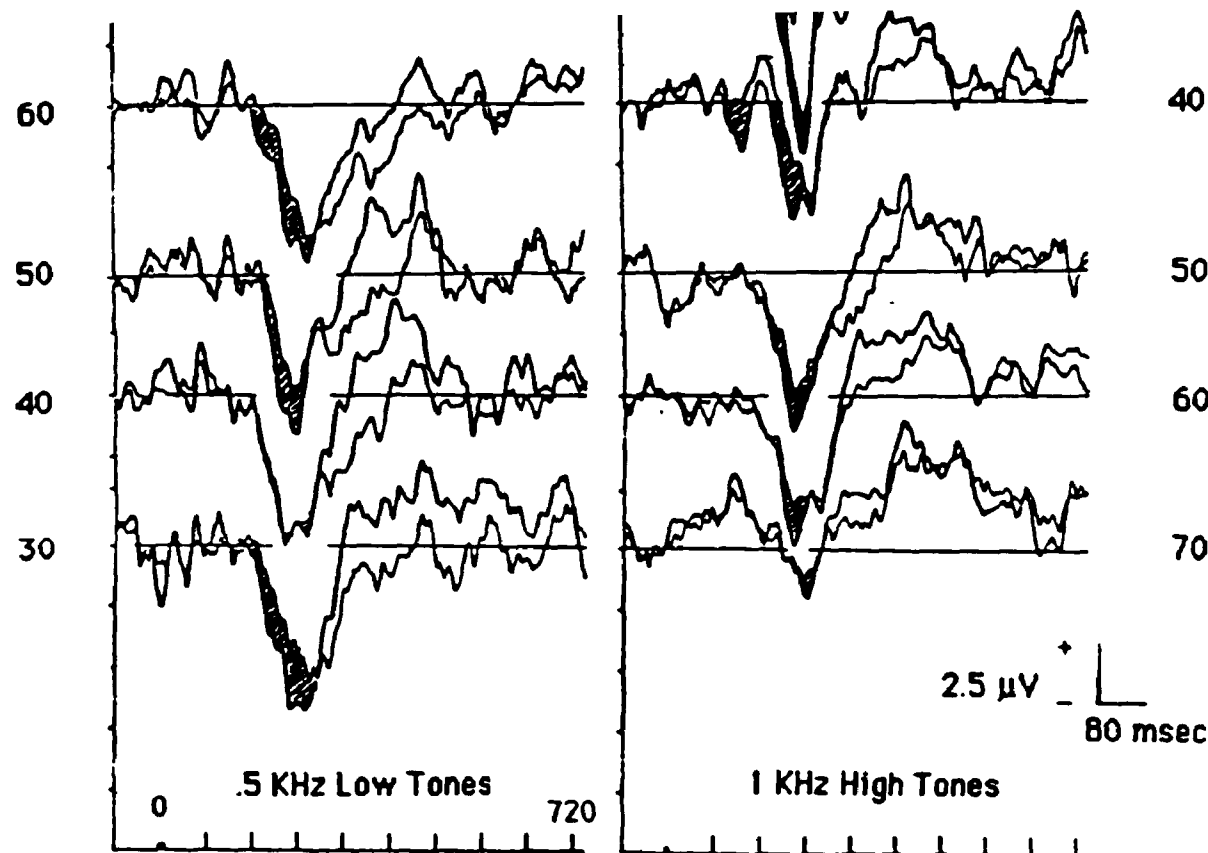


Figure 3. Effect of channel probability on processing negativity. All waveforms are Nds (as attended standard - as unattended standard). Horizontal lines represent zero μ volts (no difference due to attention). Any point below was more negative when attended. Fz and Cz electrode records are superimposed. The shaded areas represent greater negativity at the Cz electrode. The latter part of the record of 10% high tones did not reproduce well, so a dotted line has been added to show the approximate path of the late negativity. Consult figure 2 for more detail, as these subtraction waveforms were derived from those grand means by simple subtraction.

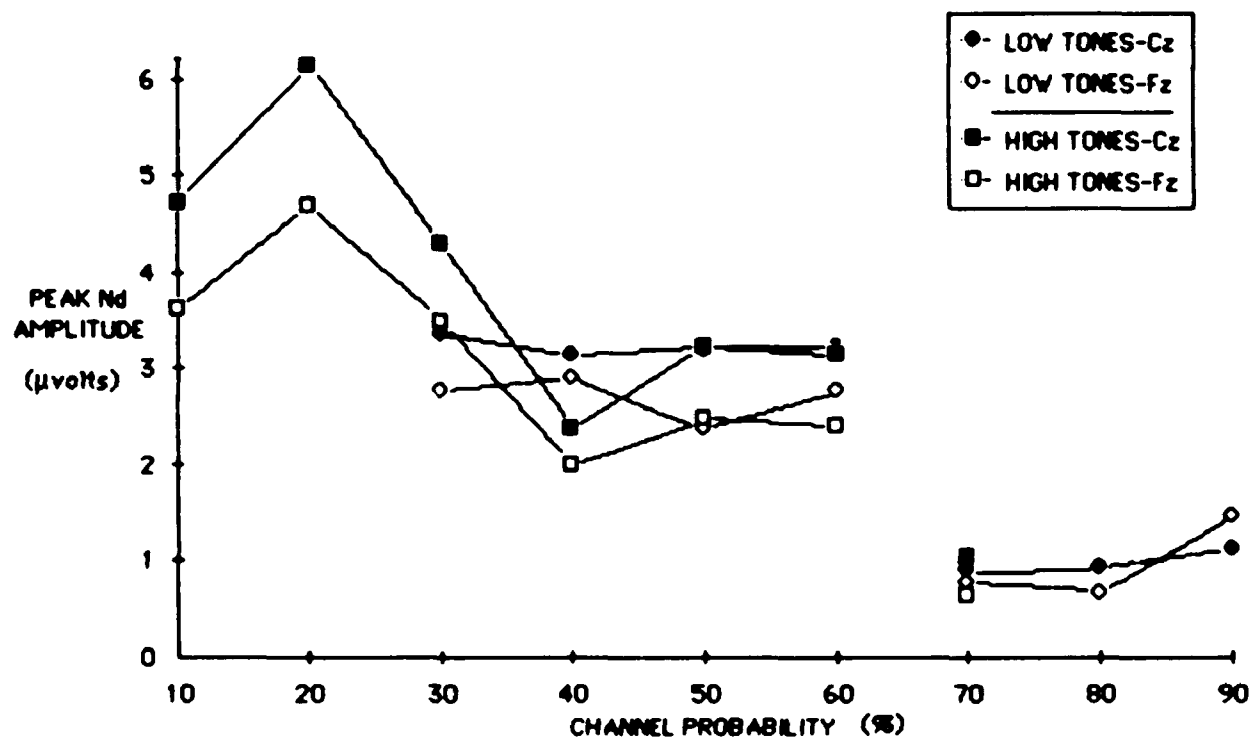
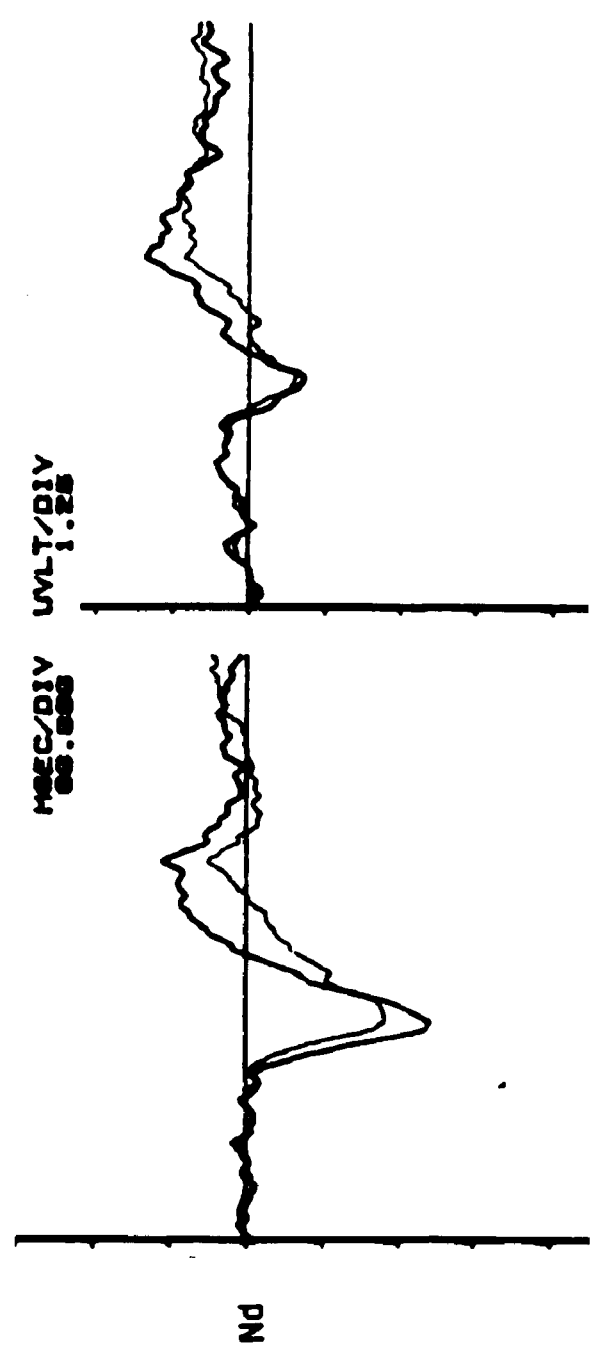
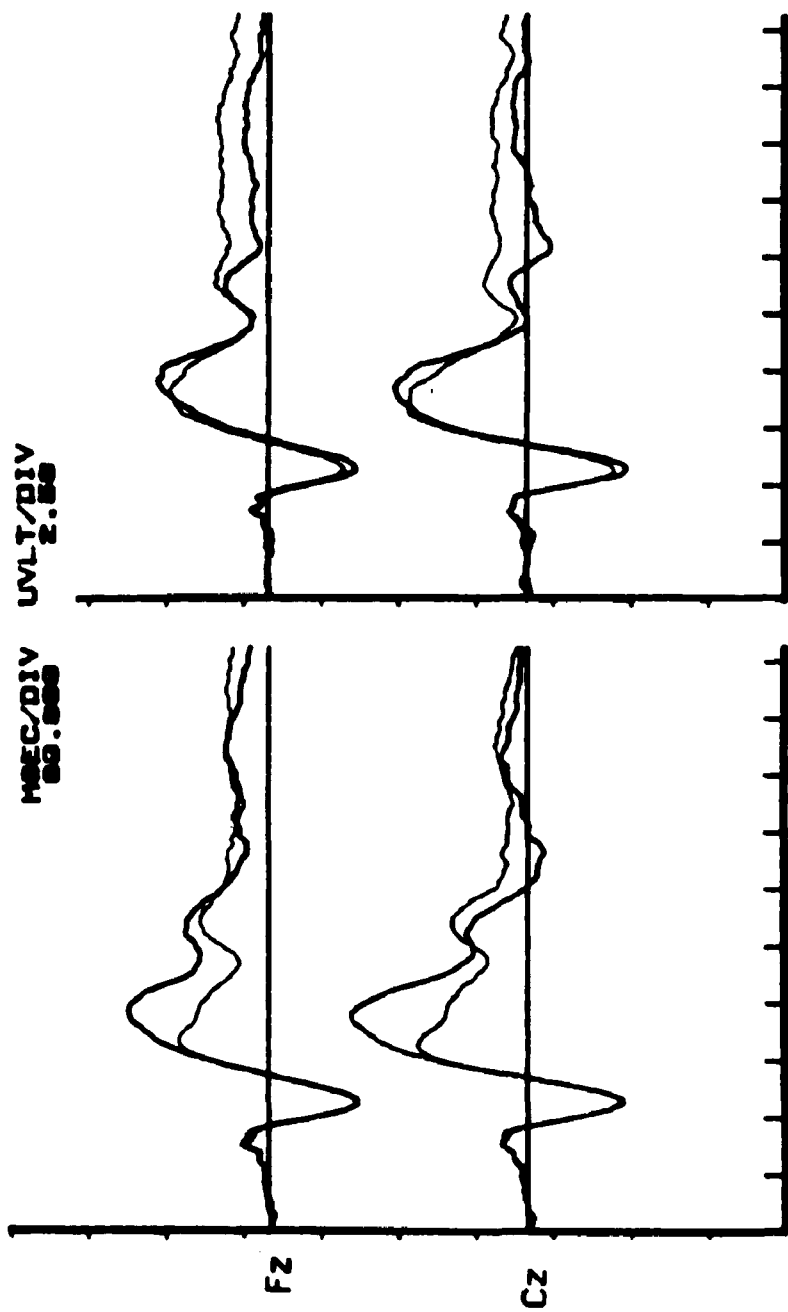


Figure 4. Peak attention-related negativity prior to 320 msec as a function of channel probability.



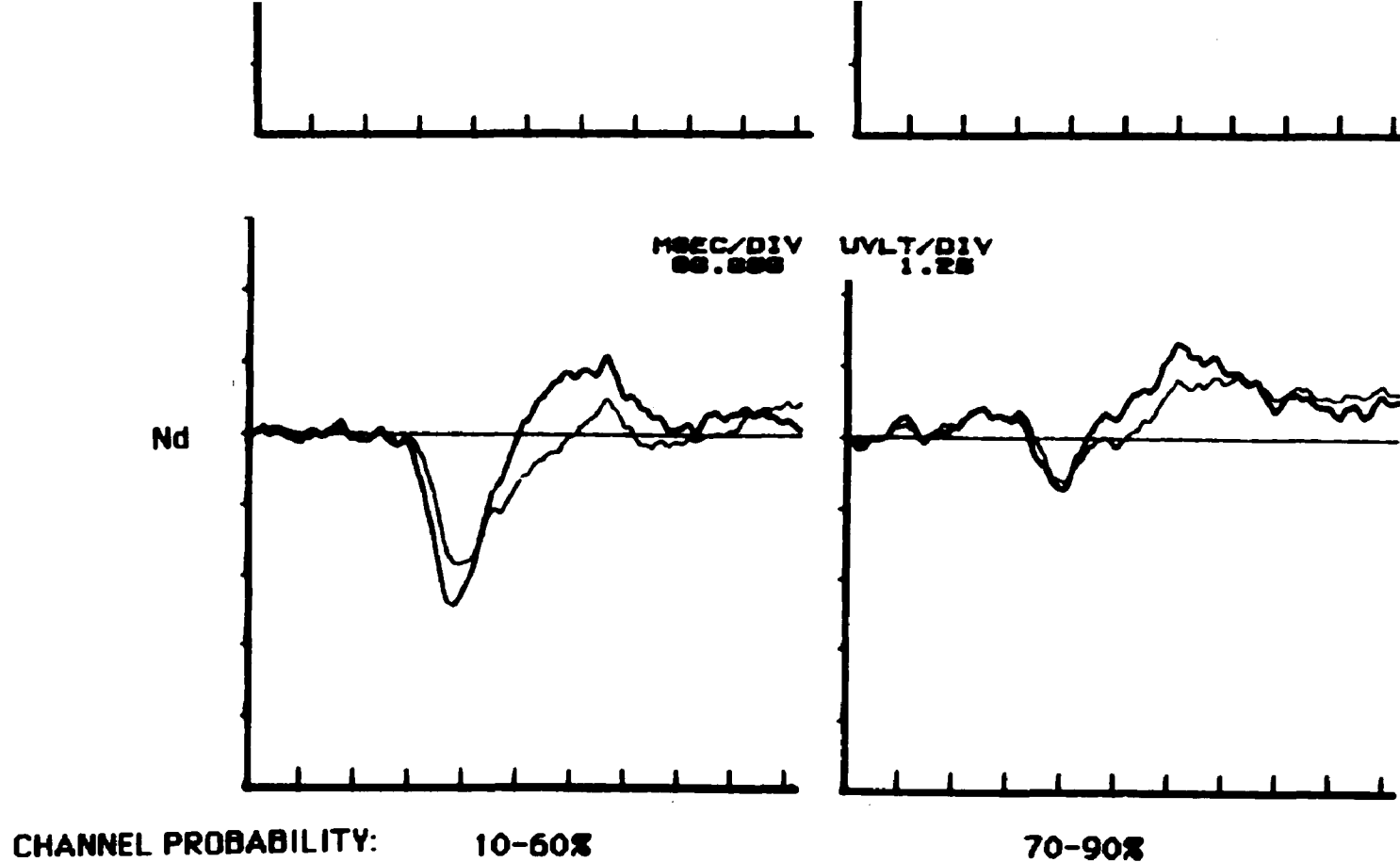


Figure 5. Grand mean ERPs for standard tones with high channel probabilities (70 through 90%) and other probabilities (10 through 60%). In the upper panel, the thin line represents attended standards and the thick line represents the same standards when unattended. The lower panel is the Nd subtraction waveform (as attended standard - as unattended standard). In the lower panel, the thin line represents the Fz electrode and the thick line the Cz electrode.

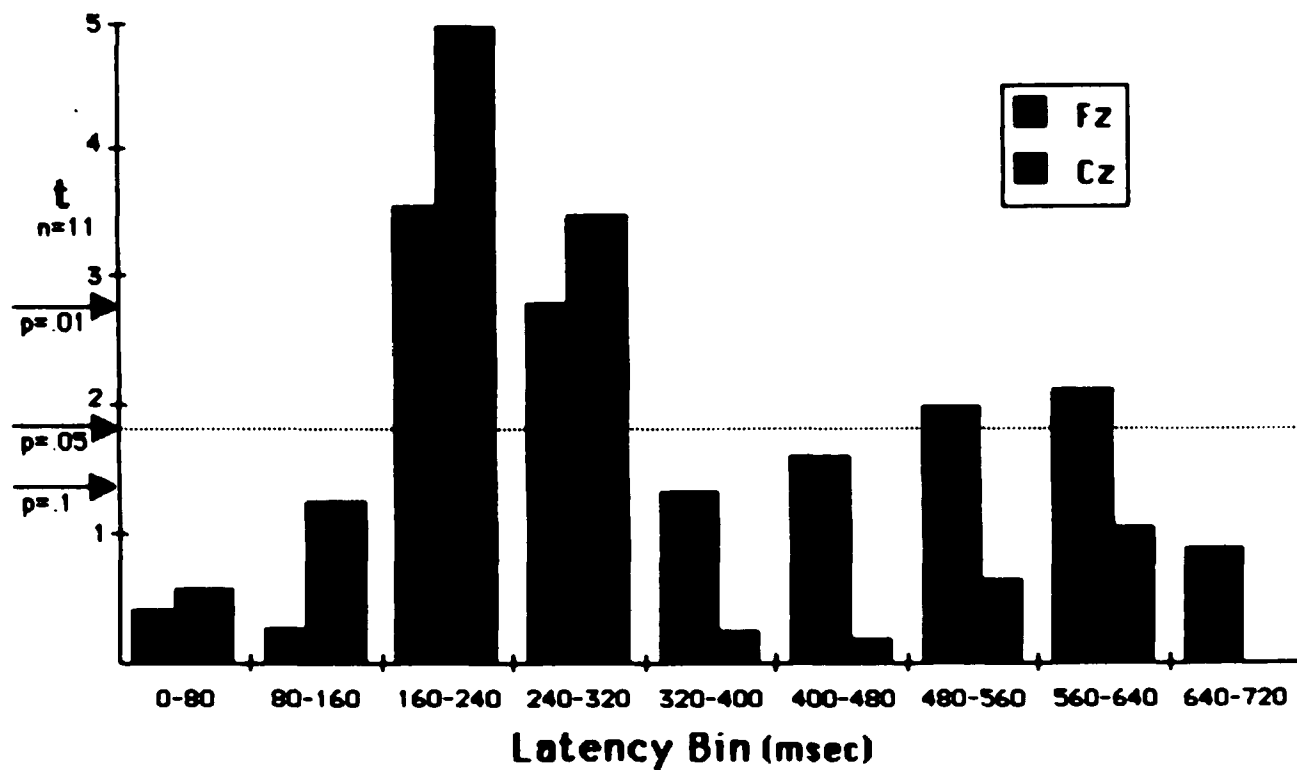
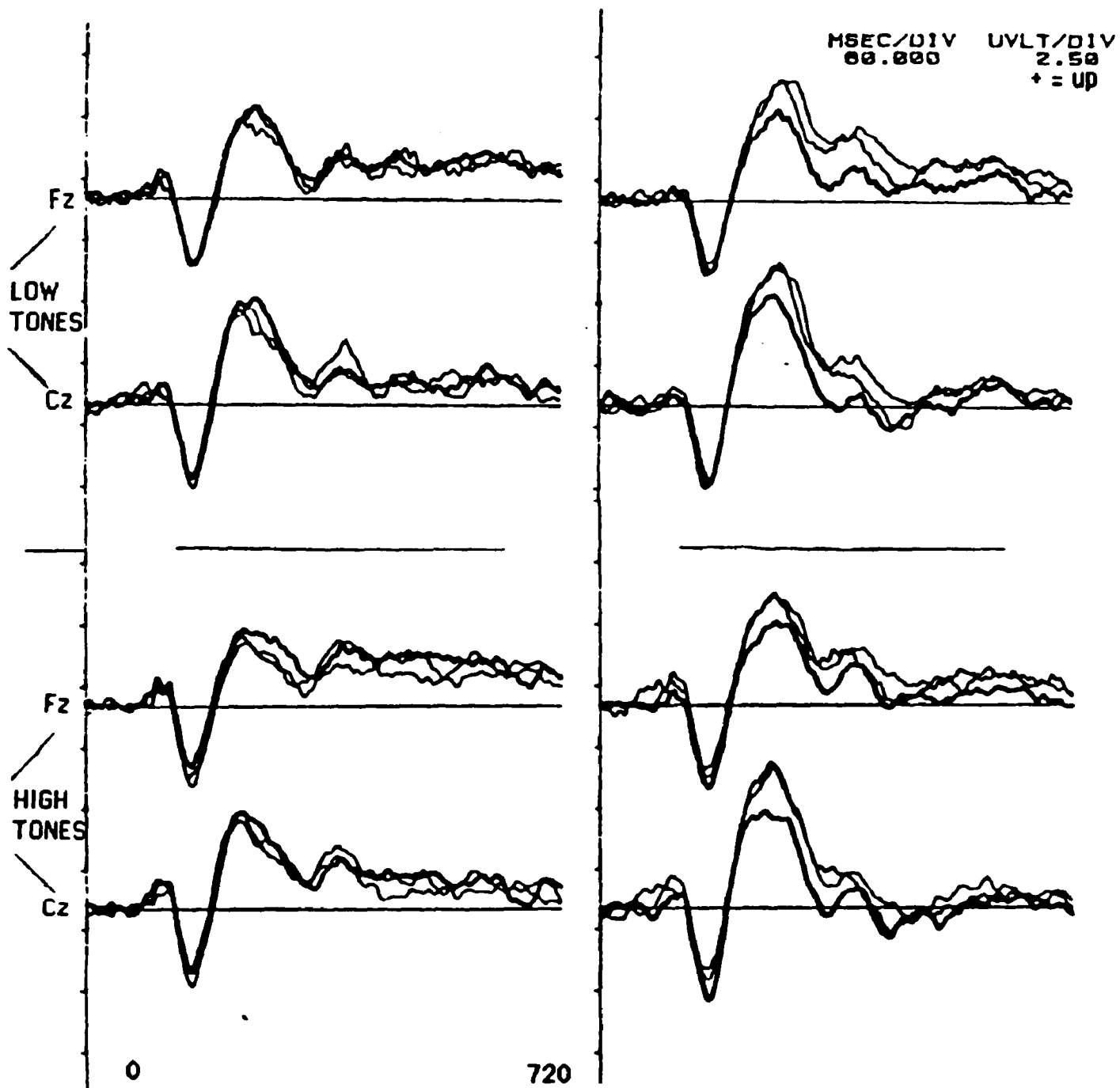


Figure 6. Timecourse of the effect of high channel probability on processing negativity (Nd). For each of the 11 subjects a summary waveform was generated for high probability Nd (70-90%) and all other standards (see figure 8). Total area of negativity was measured in each latency bin and compared in separate t-tests to test the hypothesis of reduced Nd with high channel probabilities. Important one-tailed values of t are shown on the ordinate.



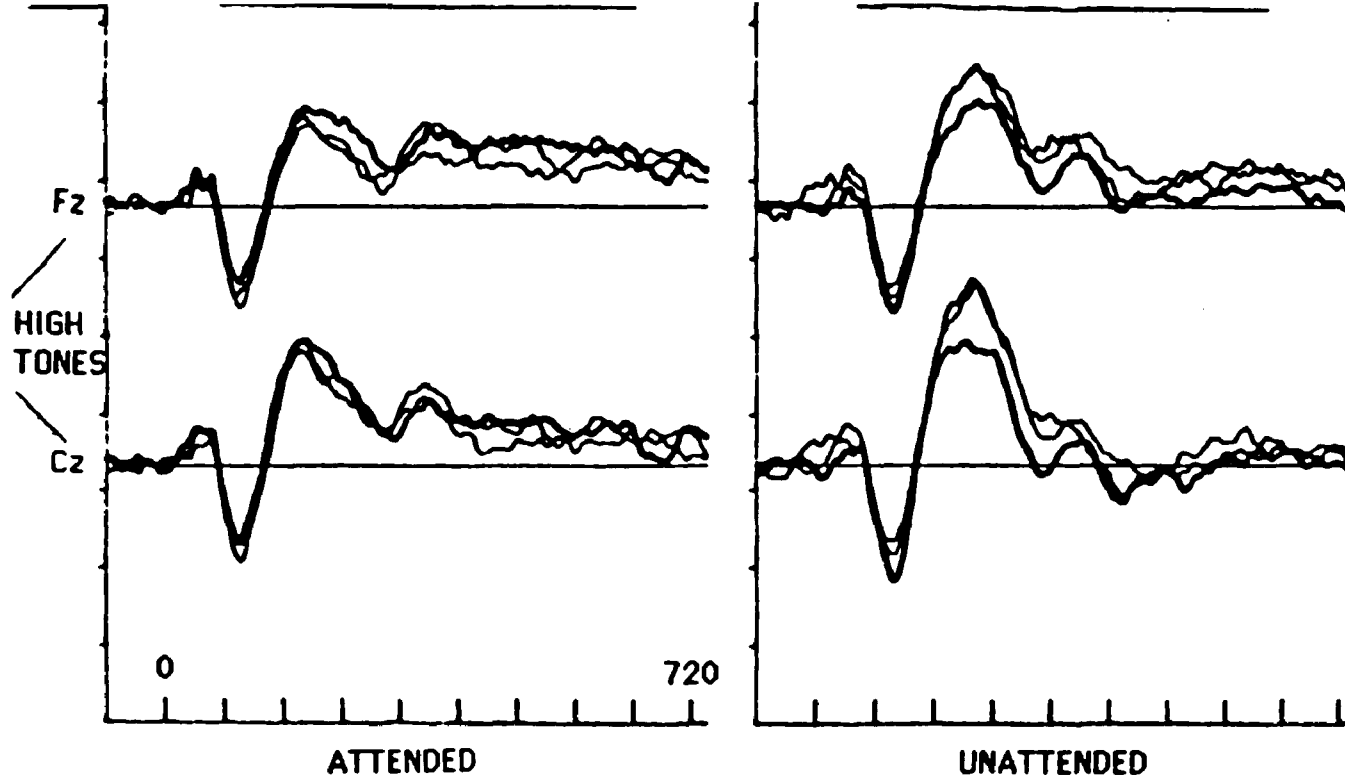
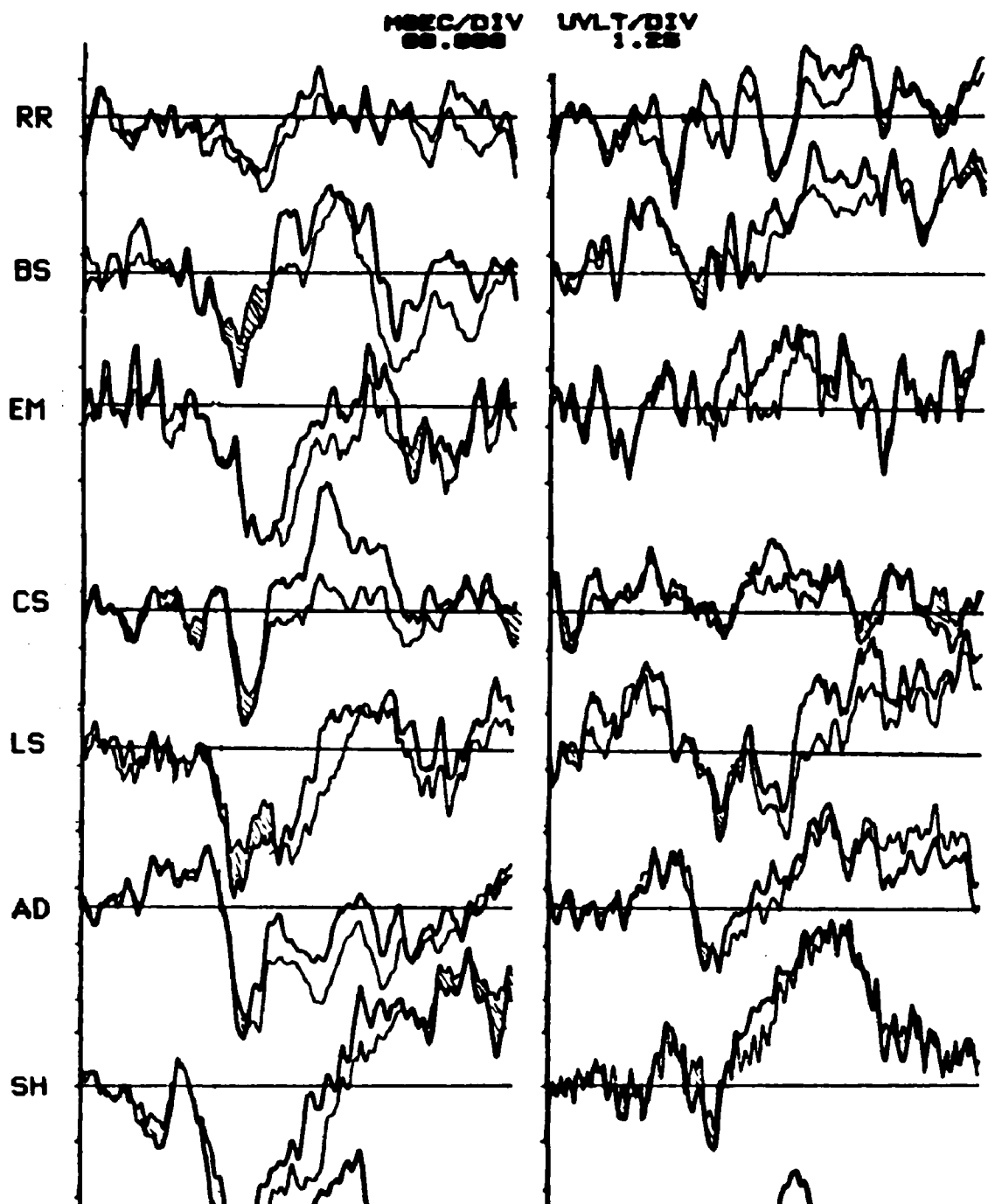


Figure 7. ERPs to .5 and 1 KHz standard tones in attended and unattended channels having channel probabilities 50, 60 and 70%. 70%=darker trace.



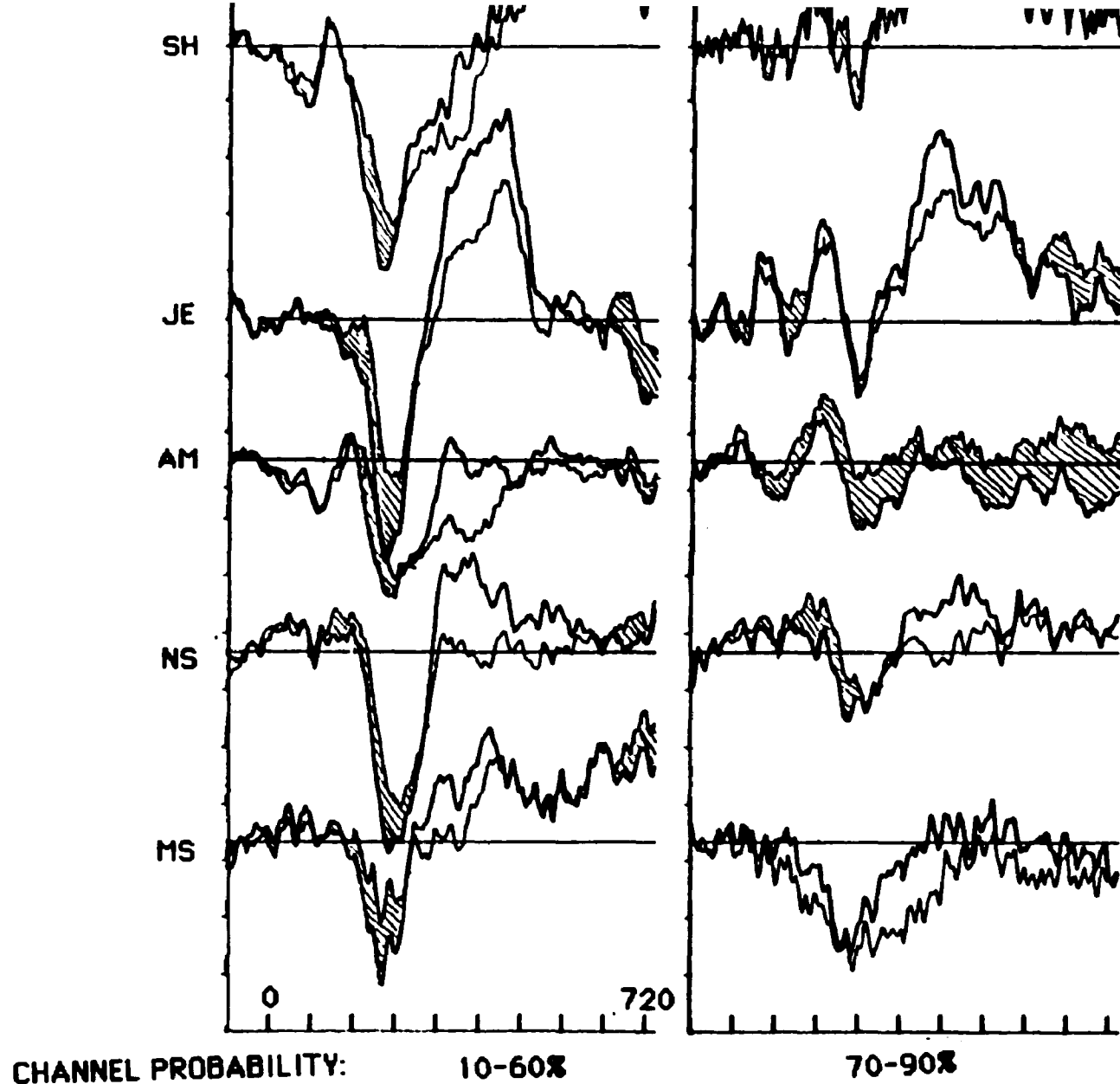


Figure 8. Individual grand mean Nds for channel probabilities 10-60% and 70-90%. The ERPs that were subtracted to yield these waveforms are presented in Appendix D. Shaded areas show greater negativity at Cz.

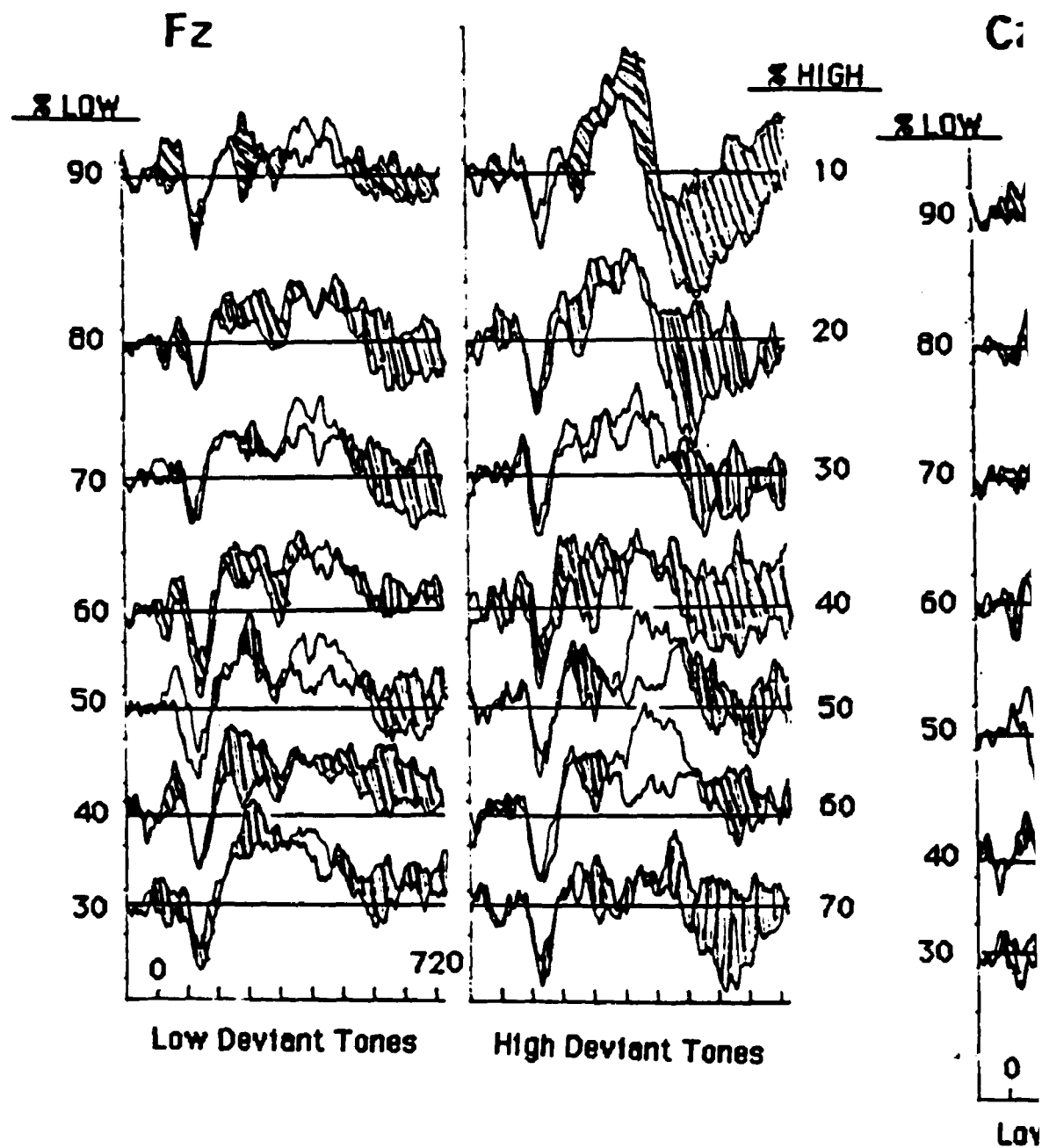
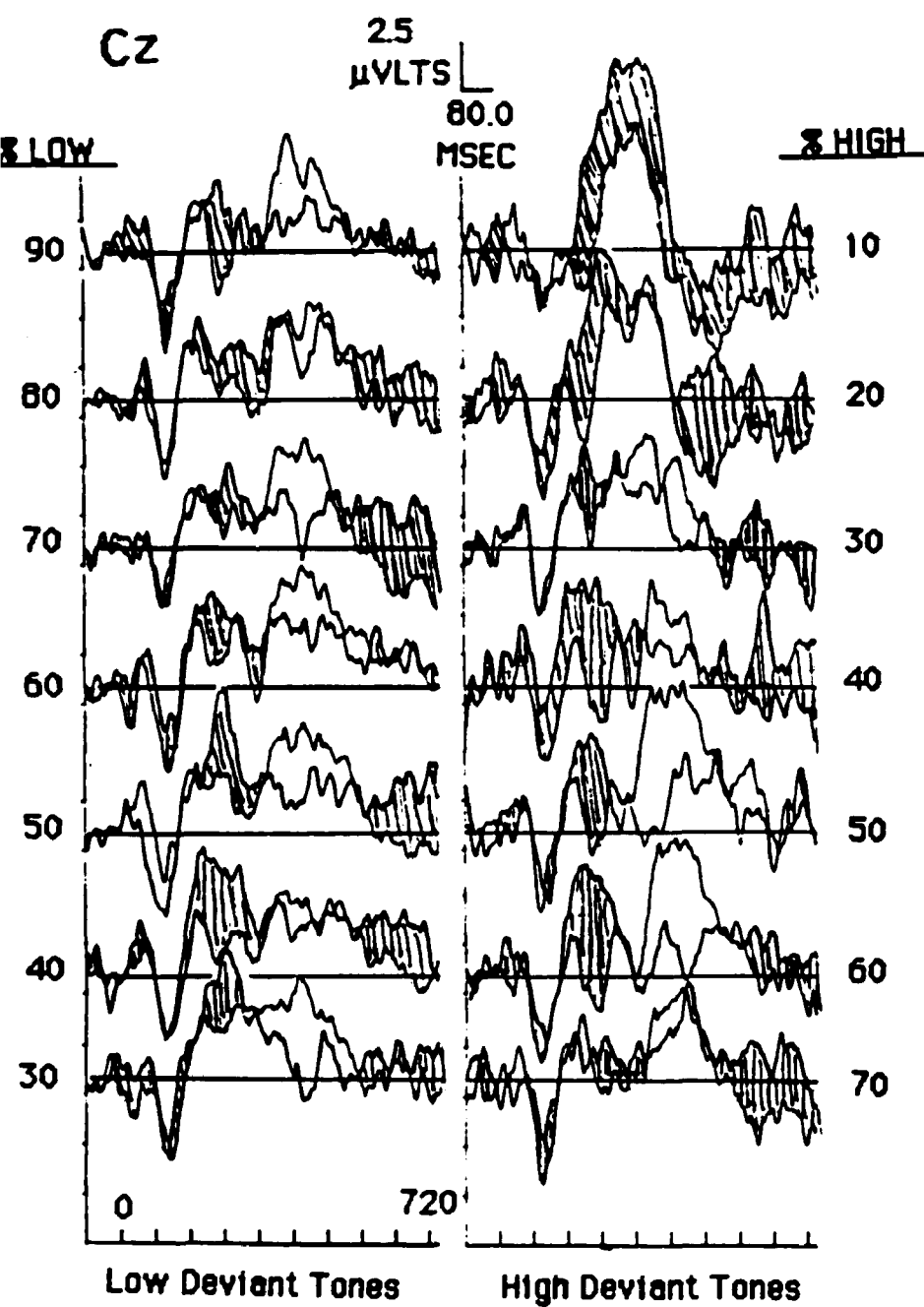


Figure 9. Grand mean ERPs for deviant long tones when attended and unattended in all channel probability conditions. Shaded area shows where attended is more negative. Cz electrode = across, Fz = above.



8 LOW TONES

MSEC/DIV 60.00

μ VLT/DIV

1.25

8 HIGH TONES

90

10

80

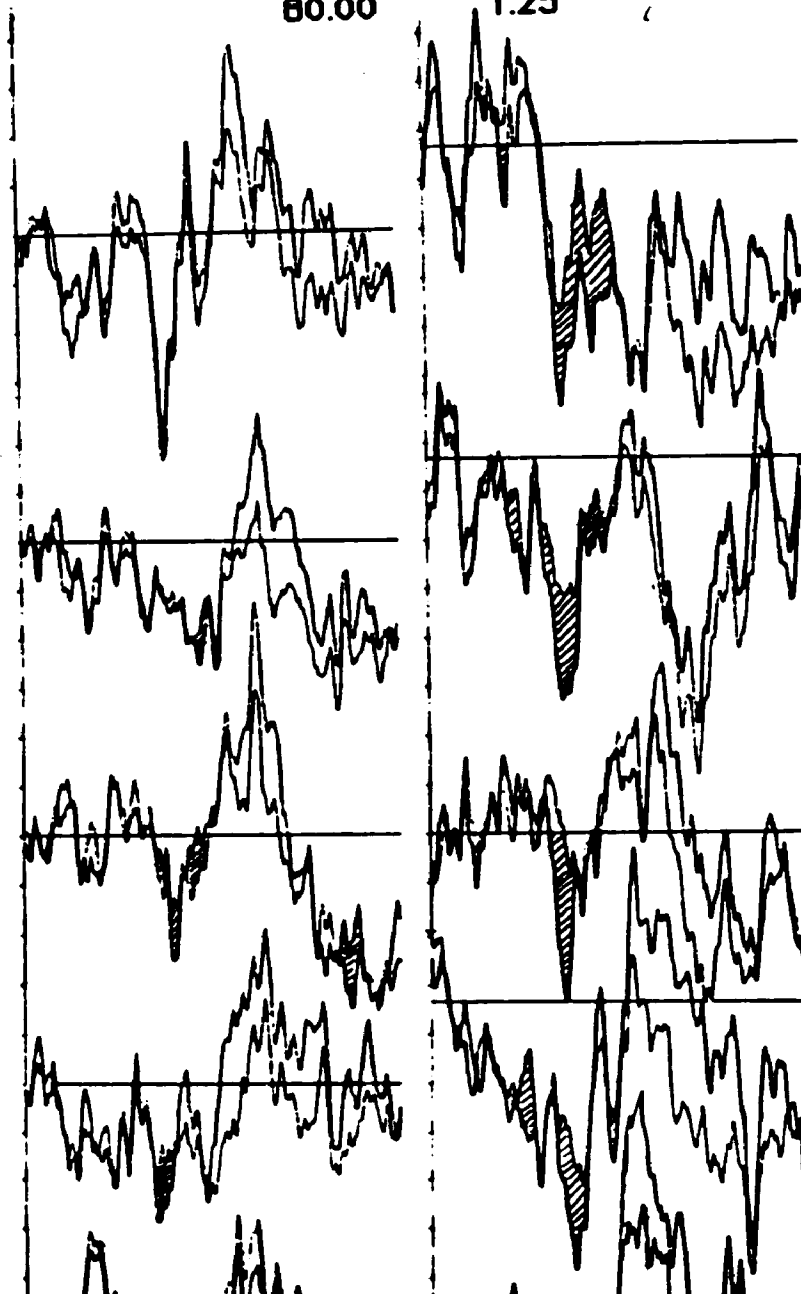
20

70

30

60

40



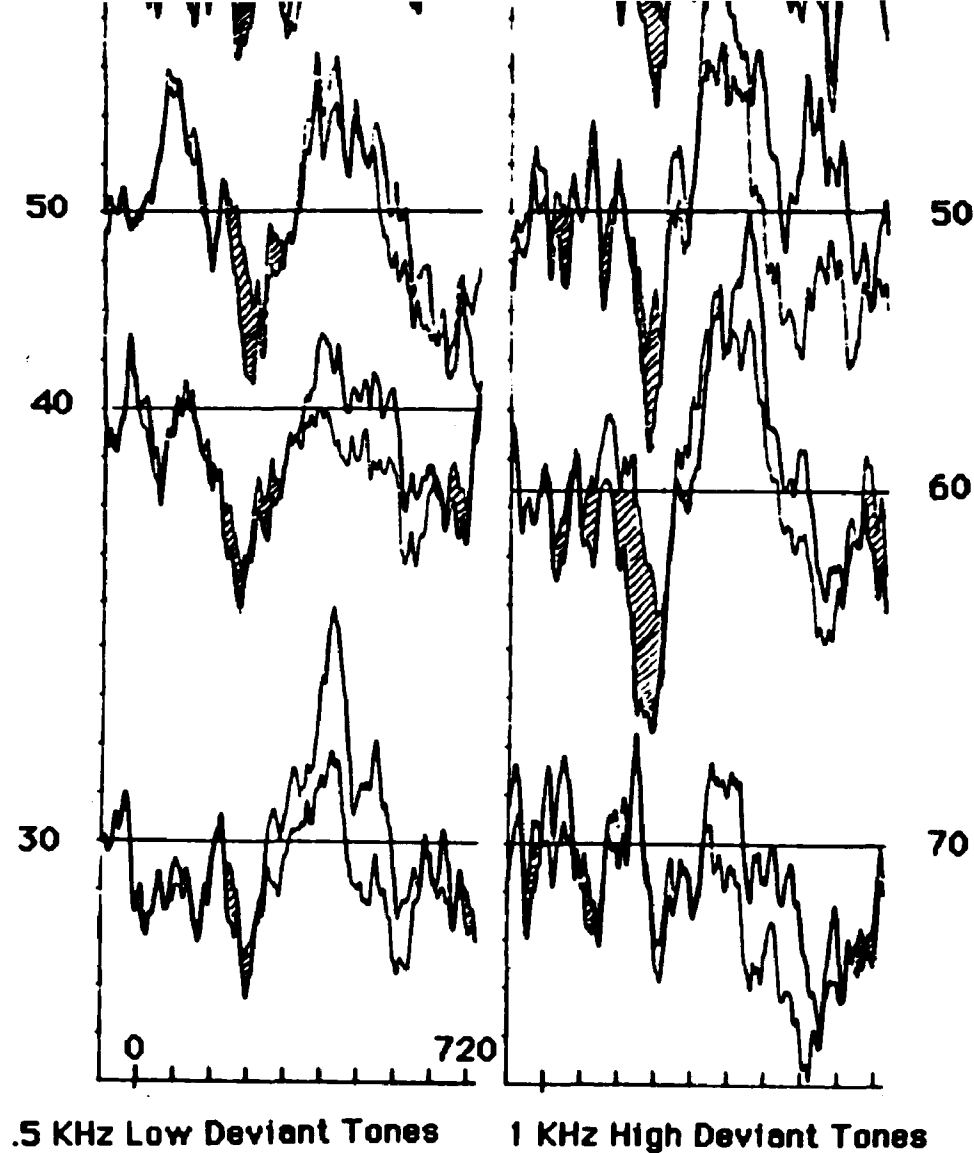


Figure 10. Effect of channel probability on attention-related negativity in the ERPs of deviant long tones. All waveforms are derived from those in figure 9 (as target - as unattended deviant). Channel probabilities are noted on the margins, although deviant probability was relatively invariant across conditions. Fz and Cz electrode records are superimposed. Shaded areas represent greater negativity at the Cz electrode.

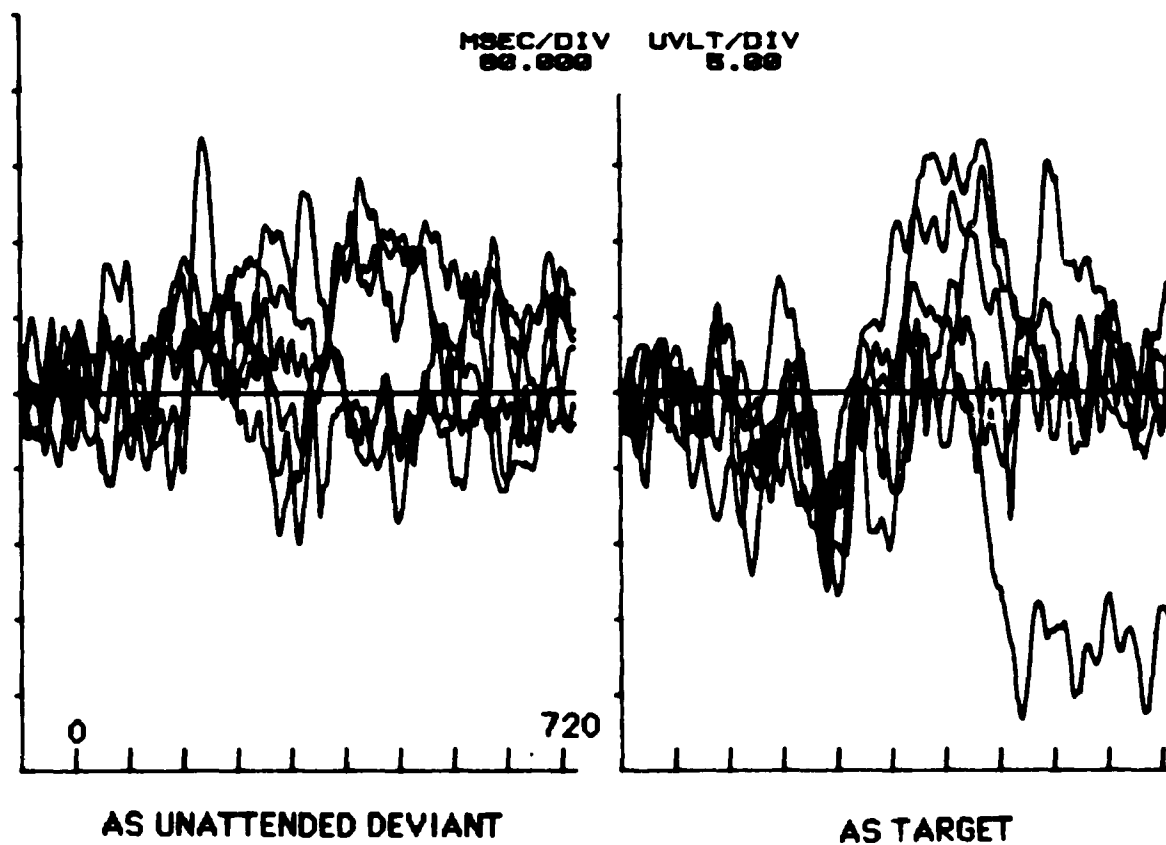
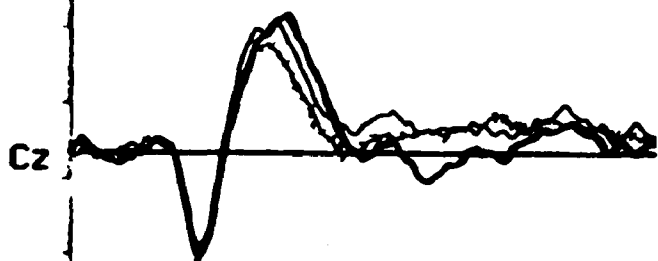


Figure 11. High deviant tone Cz ERPs where channel probabilities were equal for six randomly selected subjects show strong Nd, but high variability over the rest of the timebase.

8 LOW



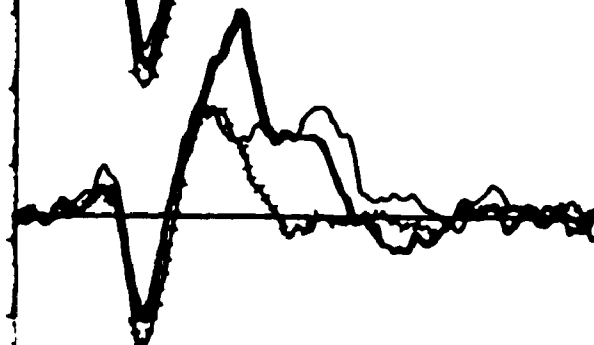
70



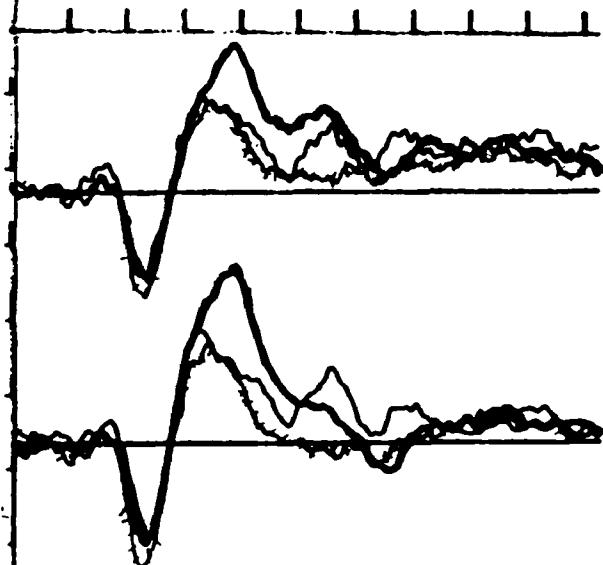
8 HIGH



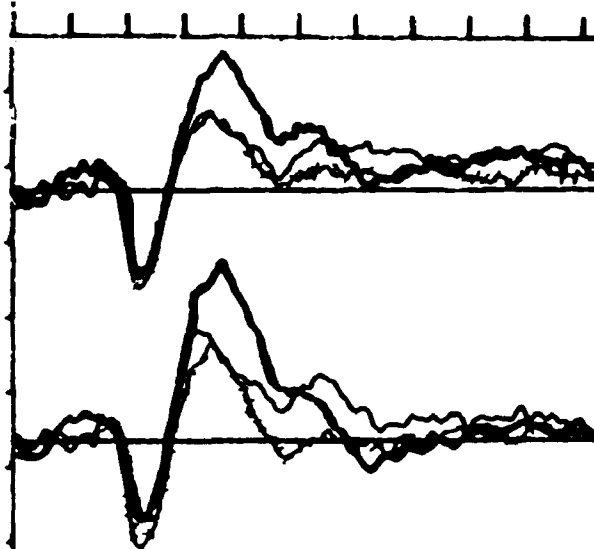
30



50



50



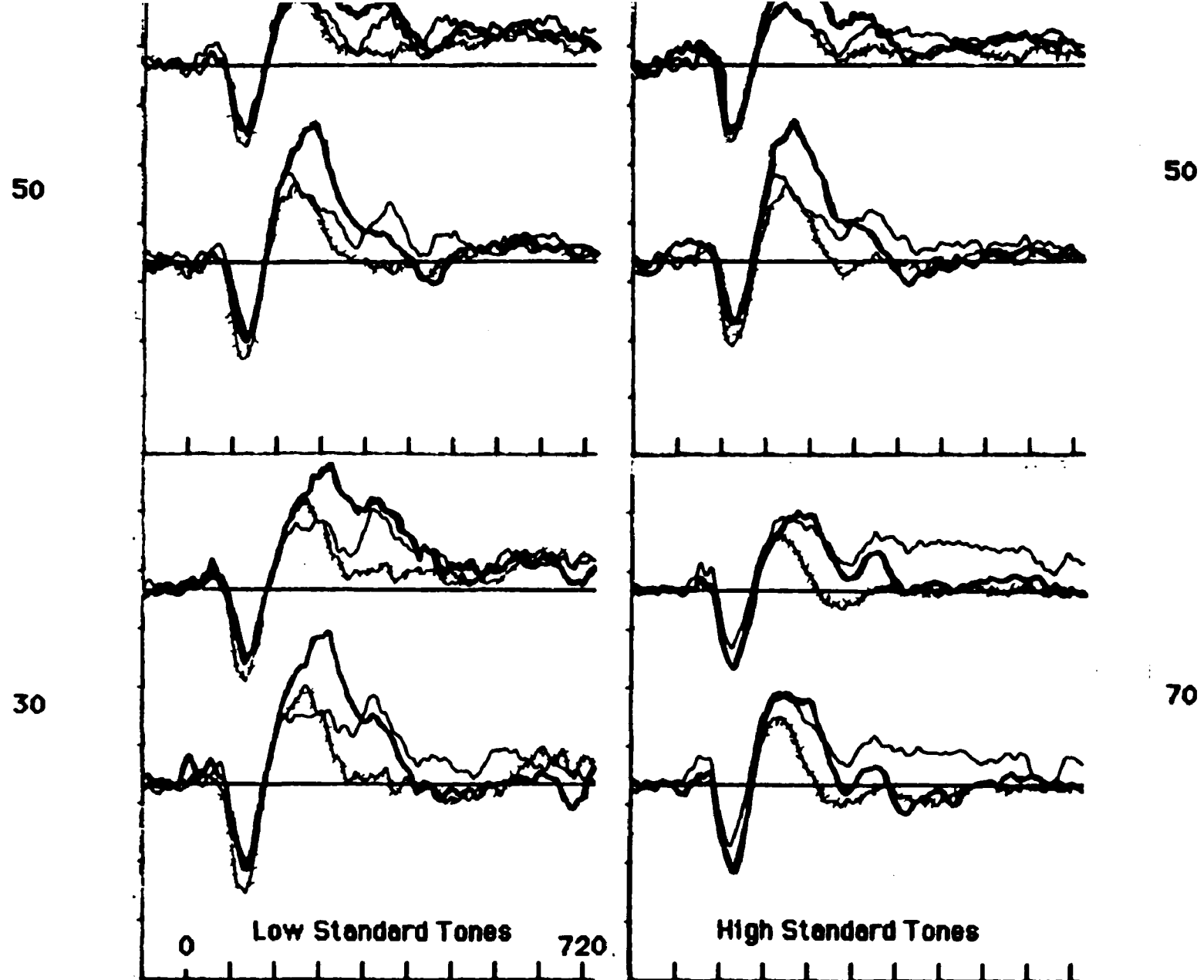
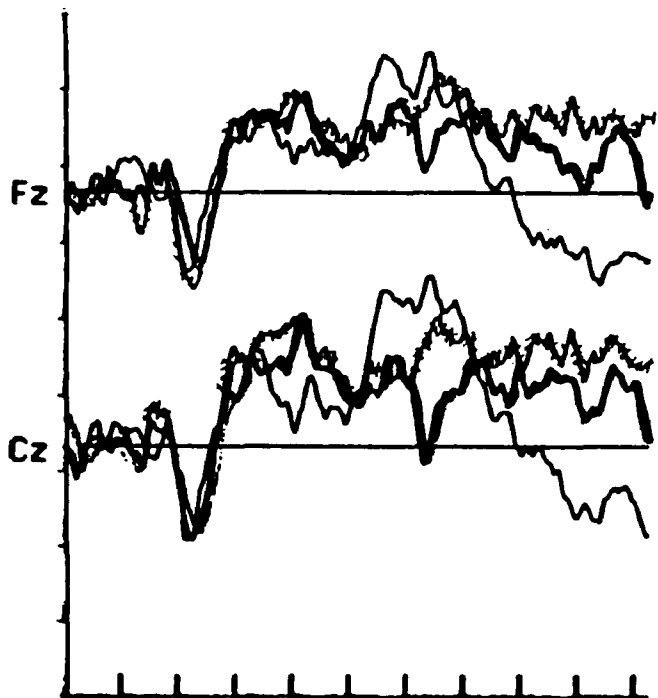


Figure 12. Grand mean ERPs for visual distractor condition standard tones. Thick and thin lines represent the auditory attention runs (unattended and attended respectively). Dashed line represents the same tones when they were irrelevant to a visual task. Fz = upper group in each panel, Cz = lower group. Scale: 80.0 MSEC/DIV, 2.5 μ V/DIV

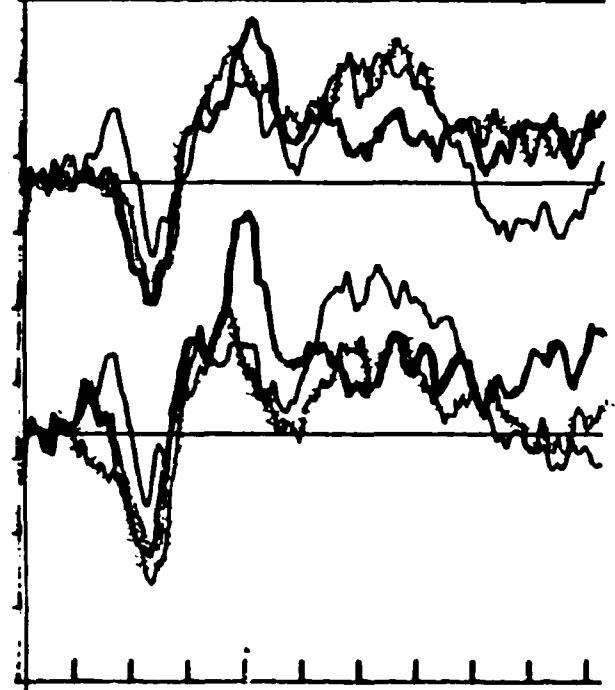
8 LOW



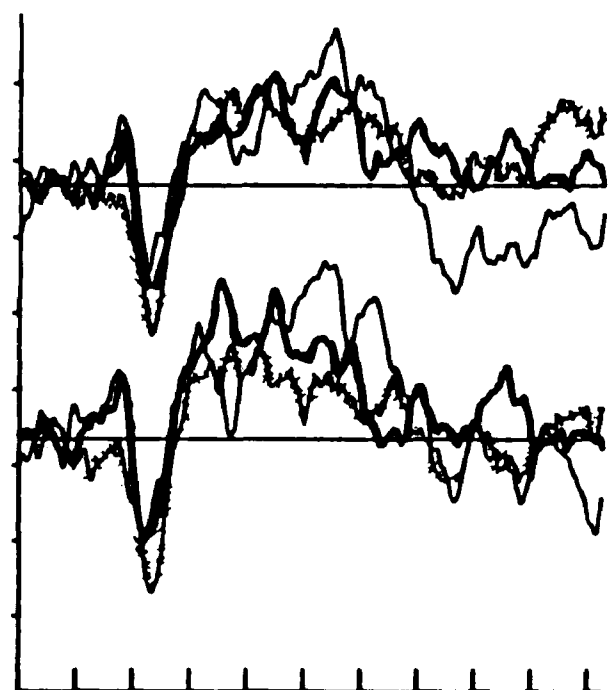
70

Cz

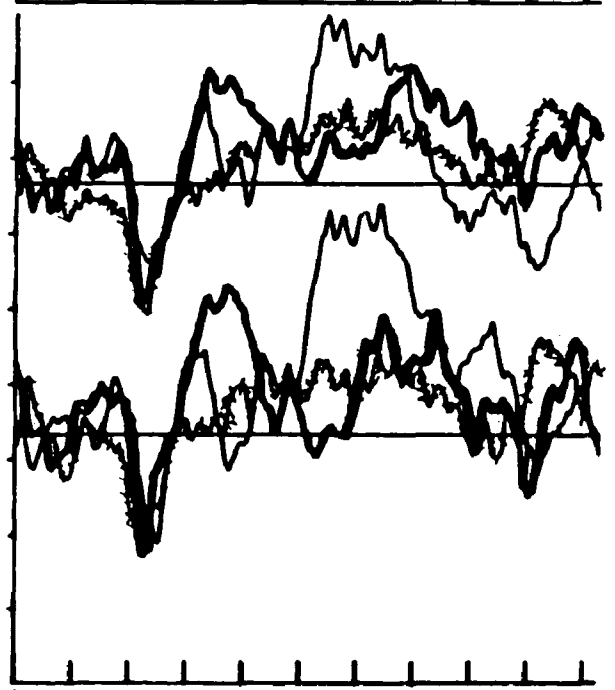
50



8 HIGH



30



50

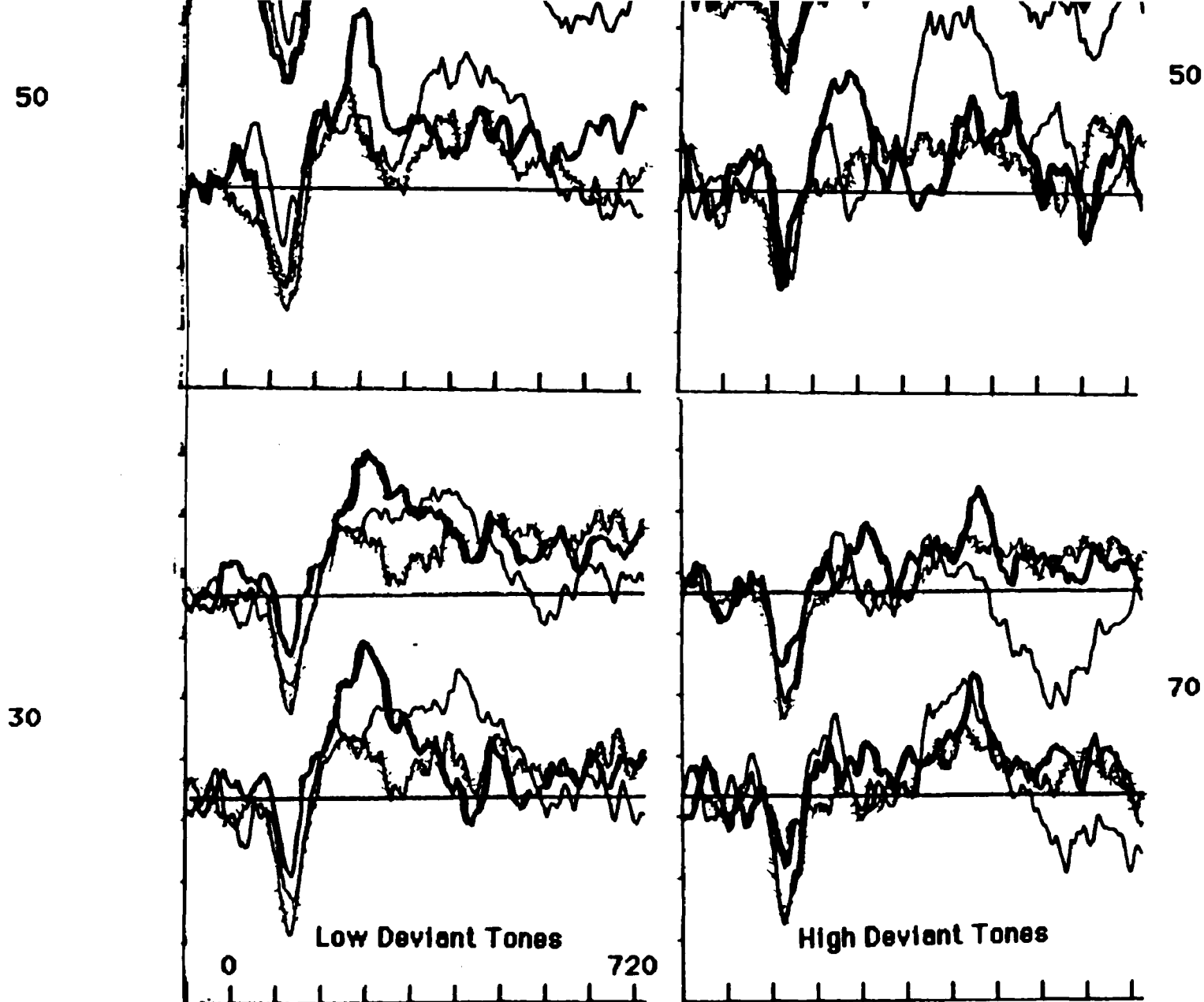


Figure 13. Grand mean ERPs for visual distractor condition deviant long tones. Thick and thin lines represent the auditory attention runs (unattended and target respectively). Dashed line represents the same tones when they were irrelevant to a visual task. Fz = upper group in each panel, Cz = lower group. Scale: 80.0 MSEC/DIV, 2.5 μ VLTS/DIV

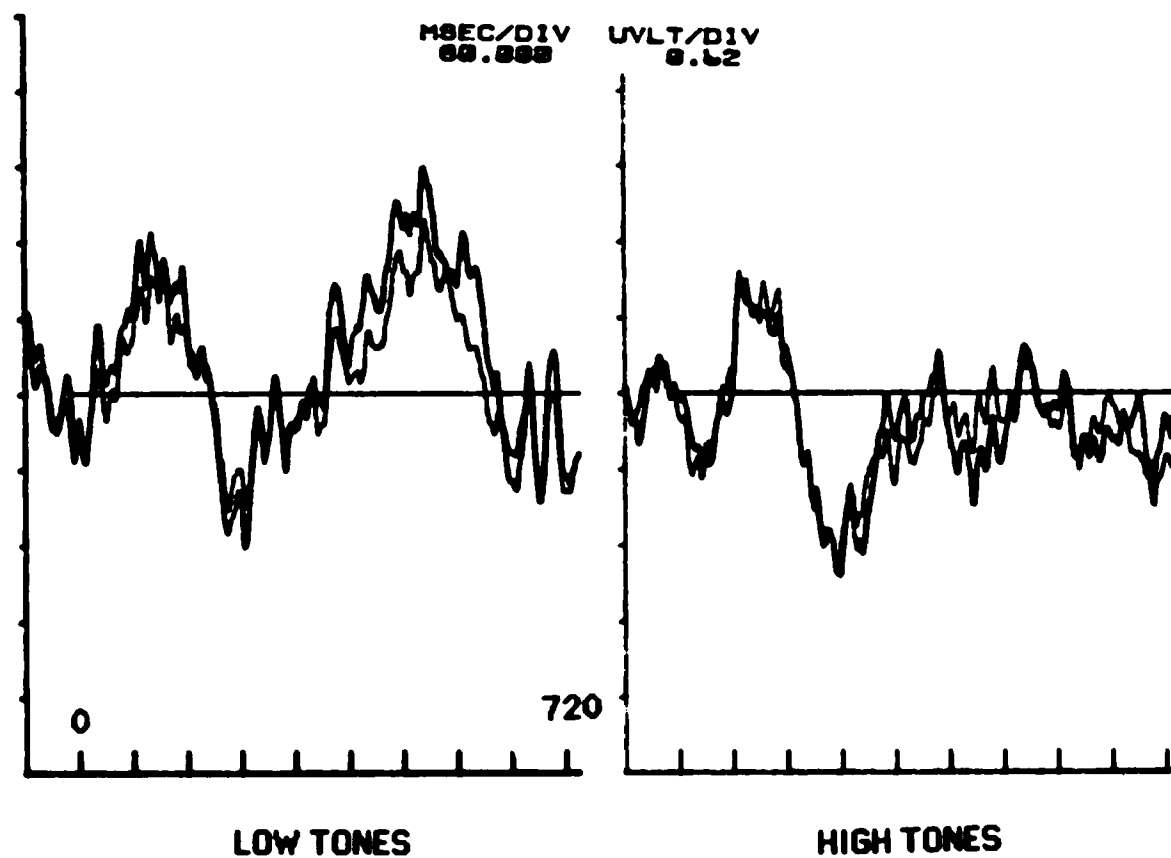
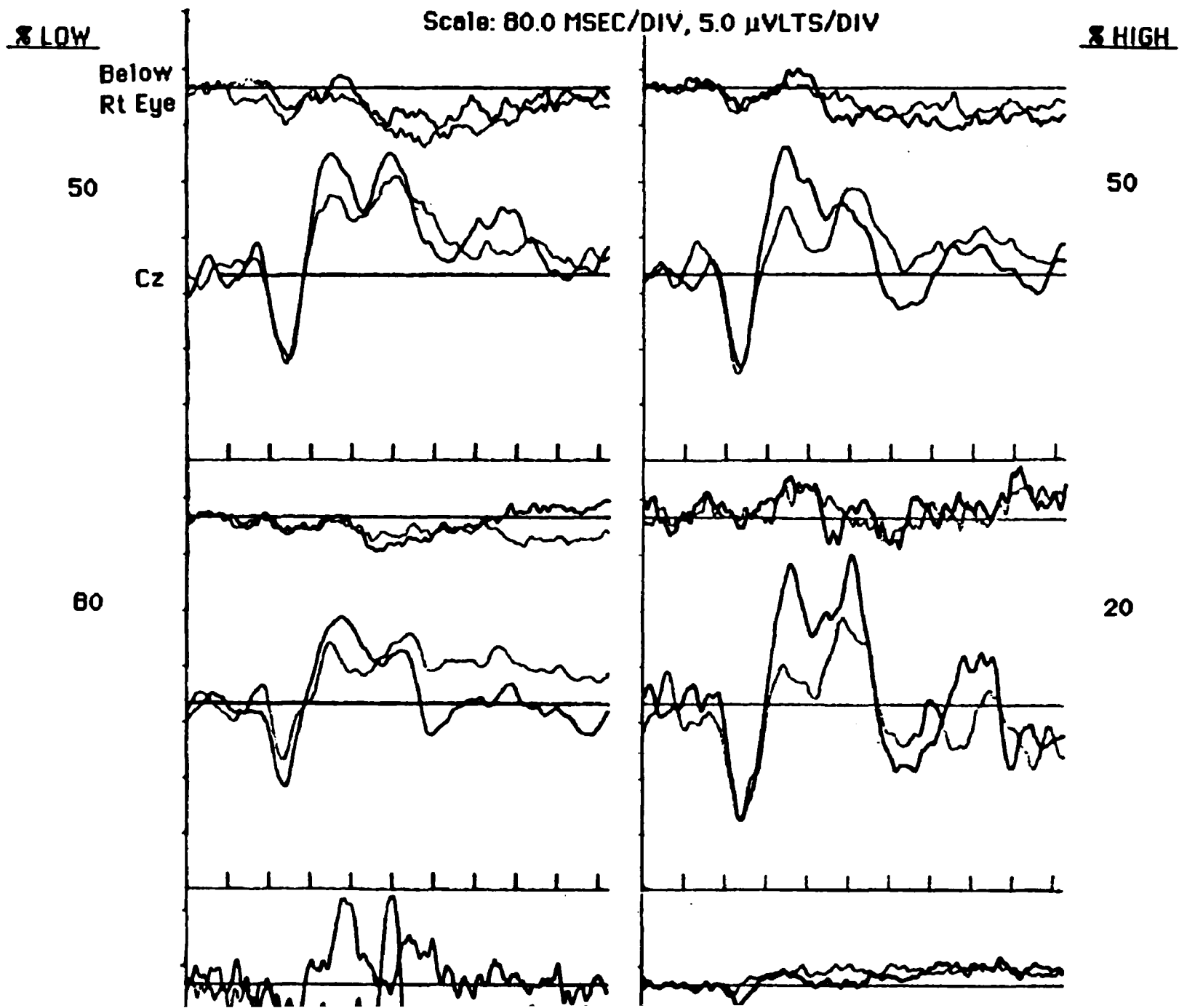


Figure 14. Grand mean event-related potentials for visual distractor control standard tones with 70% channel probability minus those with 30% channel probability demonstrates pitch-specific refractoriness. Cz electrode = thick line, Fz = thin line.



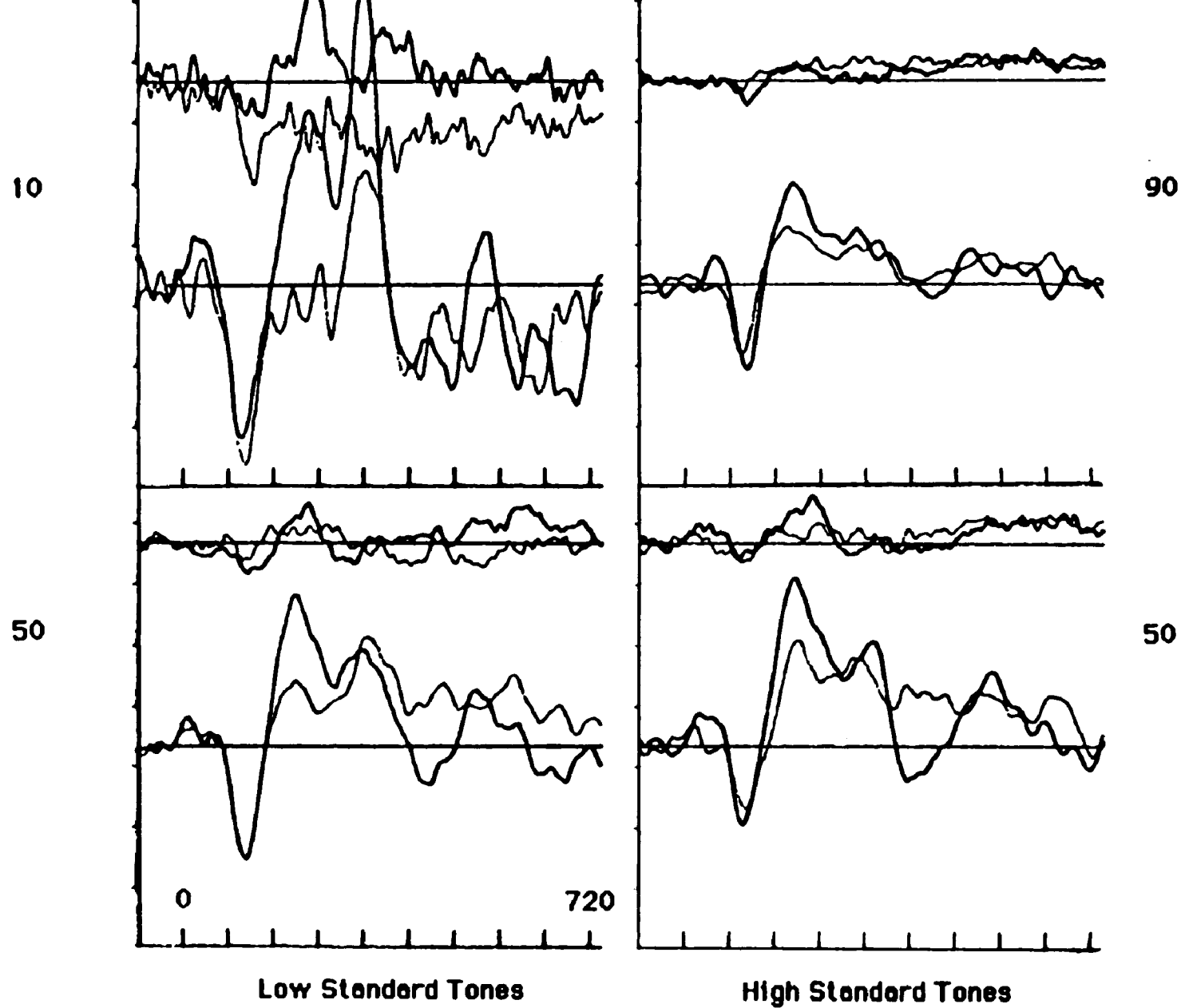


Figure 15. ERPs for standard tones in ocular control EN. Each of the 4 runs is shown with order of presentation going down. For each panel, the upper traces represent an electrode under the right eye and the lower traces are Cz. Light line = attended, dark = unattended.

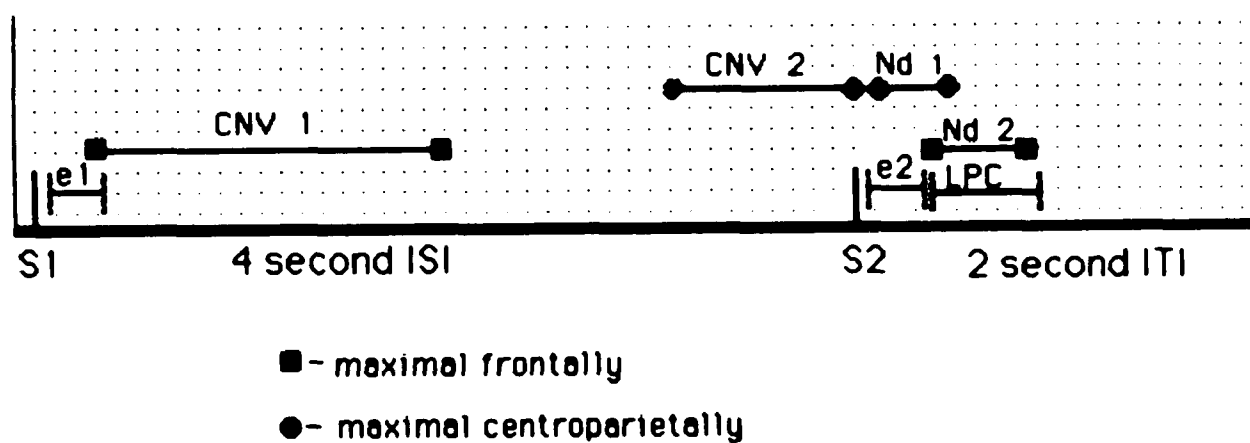


Figure 16. Temporal relationships of human event-related potentials in a cued oddball paradigm where a target followed the cue. Component groups e1 and e2 represent the exogenous potentials produced by the cue (S1) and the target (S2). All other components are related to attention. CNV and Nd are divided into early (1) and late (2) subcomponents. CNV 1 and Nd 2 reach maximum amplitude frontally while CNV 2 and Nd 1 show maximum amplitudes over posterior areas and modality-specific sensory cortices. Late positive component (LPC) can be differentiated into multiple subcomponents, discussed in the text. ISI = inter-stimulus interval. ITI = inter-trial interval.

TABLE 1.

NOT MEASURED AS NEGATIVE AREA FROM 80-480 MSEC FOR CHANNEL
PROBABILITIES 10-60 AND 70-90%

		<u>Cz-NOSE</u>		<u>Fz-NOSE</u>	
		<u>10-60</u>	<u>70-90</u>	<u>10-60</u>	<u>70-90</u>
1.	JE	2.13	.28	1.27	.20
	JE (pII*)	275	37	165	26
2.	LS	1.92	.63	2.03	.82
3.	EM	1.83	.00	2.55	.09
4.	SH	2.79	.24	3.00	.09
5.	NS	1.86	.50	1.45	.34
6.	AD	1.22	.32	2.02	.41
7.	BS	0.85	.09	0.65	.00
8.	CS	0.69	.05	0.63	.06
9.	AM	1.84	.83	2.39	.07
10.	RR	0.56	.53	0.89	.81
11.	MS	1.02	1.23	0.52	2.67
		WILCOXON $T_{Cz}=2$ $p<.005$		$T_{Fz}=8$ $p<.025$ (1-tailed)	

*Note. These are area measurements made by the Pathfinder II Int software program found on the extended library disk. All other measurements in this table were made with the polar planimeter.

Appendix C

Additional Subject Information

INIT.	DATE	PLA	ERRORS	ADDITIONAL SUBJECT INFORMATION
MS	7/30	75	-3/8	L. handed, Binary tholds=10(.5 KHz), -8(.5)
	8/5	65	-4+1/6	Counted on fingers all but last 2 of day 2!
CS	7/13	80	-18+1/8	Lo 90*, high artifact and alpha-like activity
	8/22	70	-9+4/6	Run 1 RR, tired
RR	7/15	80	-27+1/8	Lo 60*, Lo reported louder + easier
	8/25	80	-17/6	Lo 70 & 90 RR, better count for HI
JE	7/24	70**	-12+4/8	Binary Tholds=14(.5 KHz), -4(1)
	8/20	80	-2+1/6	Unattended long intruding on attention
AM	7/29	80	-4+7/8	Age 18, Binary Tholds=27!!(.5 KHz), -6(1)
	8/9	75	-8+5/6	
LS	7/20	80	-4+5/8	Binary Tholds=10(.5 KHz), -2(1)
	8/13	65	-4+5/6	Had 14 minutes practice before starting
AD	7/22	75	-14/8	Hi 90*, Binary Tholds=8(.5 KHz), -8(1)
	8/8	75	-14+7/6	Tired(6hrs sleep), up to 19% artifact
SH	7/19	70	-8+1/8	Thold=10(.5 KHz)
	8/6	60	-7+3/6	Practiced 8 minutes
EM	8/10	90	-4+5/8	Age 47, Tholds= 10(.5 KHz), 0(1)
	8/12	90	-3+2/6	High artifact
BS	7/30	85	-15+17/8	Age 39, Tholds=-4,-2, Finds it difficult
	8/27	85	-10+1/6	
NS	8/3	75	-3+2/8	Sleepy, practiced 10 minutes
	8/18	70	-8/6	Practiced 6 minutes

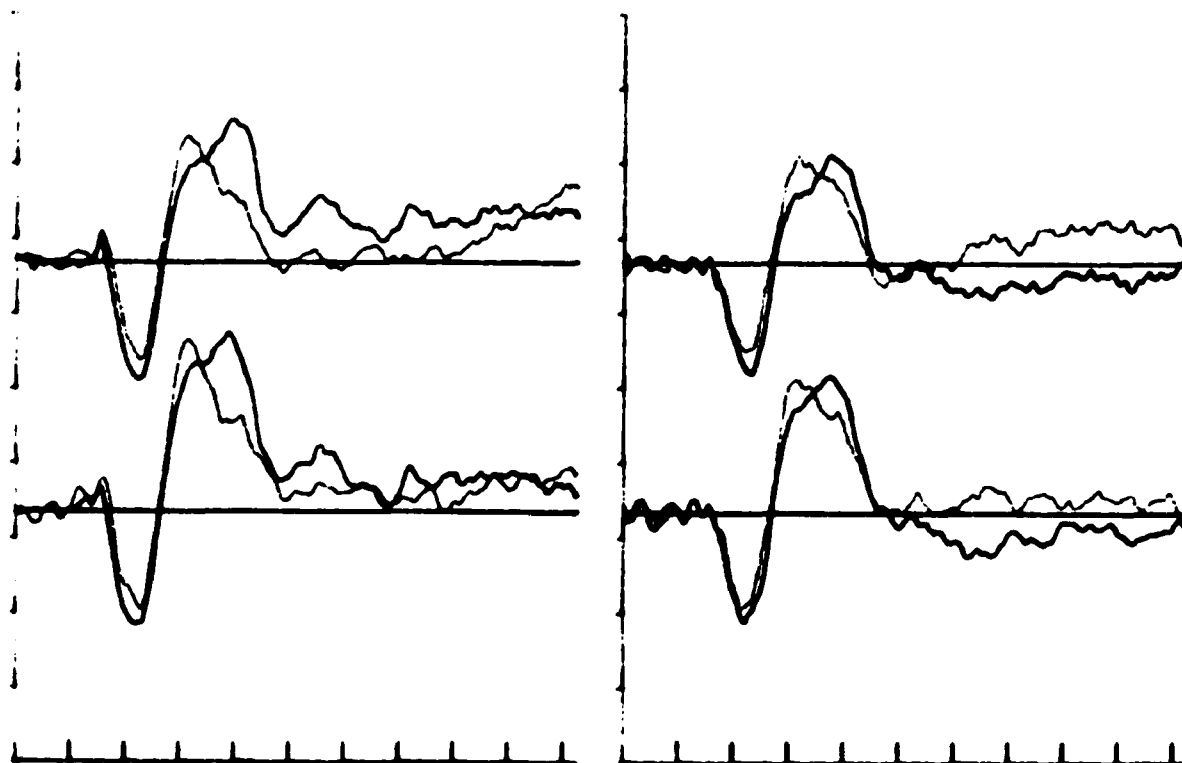
-
- ERR = Errors reported as total number of undercounts and then overcounts over total number of runs. Example: report of 5 tones when there were actually 7 yields -2.
- PLA = plateau duration of deviant long tones in msec
- * = should have been rerun for poor counting performance
- RR = rerun
- ** = Had to change to 80 for the last two runs.

Appendix D

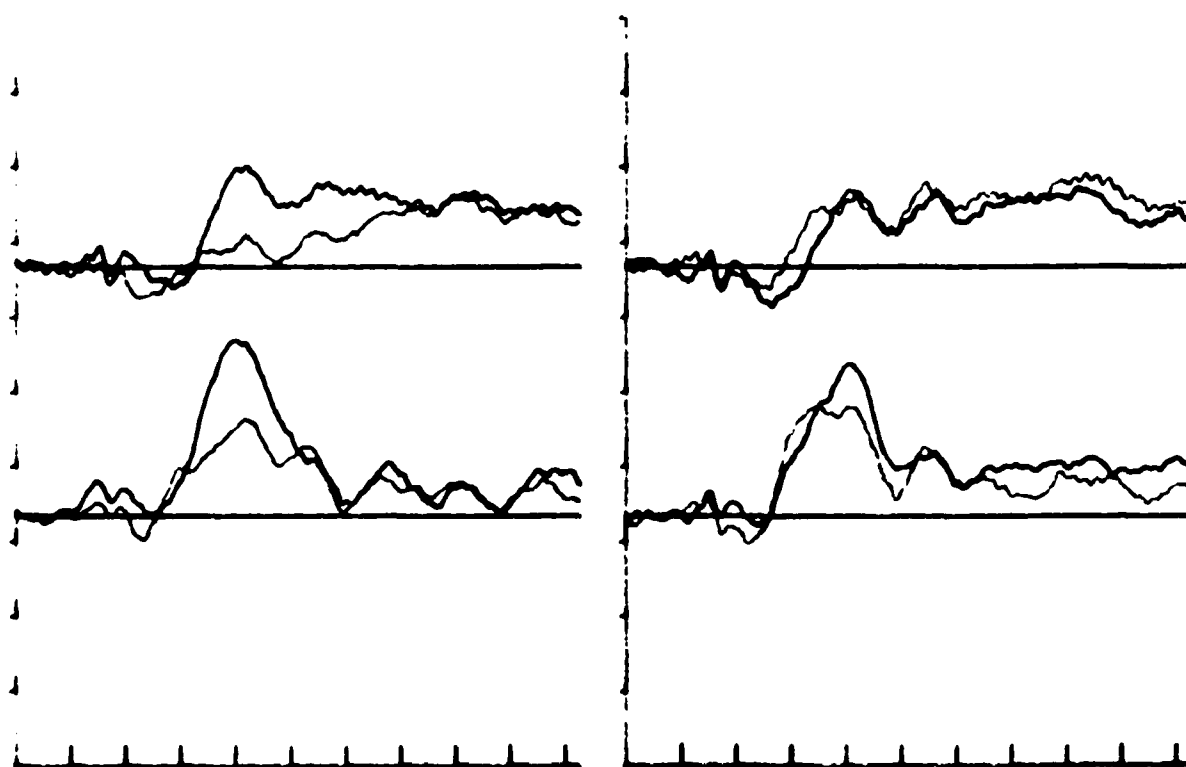
Individual Subject ERPs for High versus Other Channel Probabilities

The following eleven pages present the individual subject grand mean ERPs for standard tones collapsed into channel probability conditions from 10-60% versus 70-90%. Subject initials are shown above. The 10-60% channel probability condition is on the left and the 70-90% channel probability condition is on the right of each page. The upper tracings on each page represent the Fz site. The lower tracing represent the Cz site. The darker line = unattended standards. The lighter line = attended standards. These waveforms were used to generate figure 8 (by subtraction of unattended from attended), and figure 6 (by t-test of Nd in each 80 msec latency bin). Figure 5 shows the grand means across these subjects. The general format of these figures follows those shown in appendix B; the first vertical line on the abscissa represents stimulus onset, positive is up, etc. The scale is 80 msec/division and 2.5 μ volts/division.

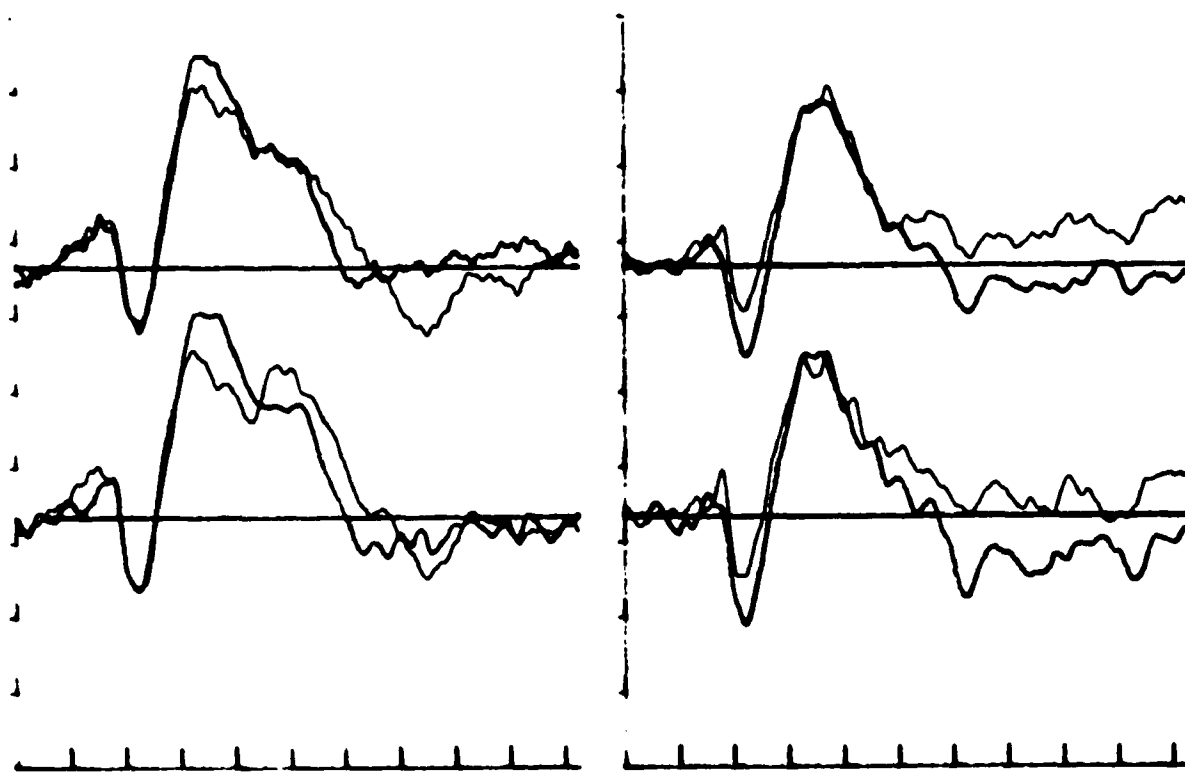
A D



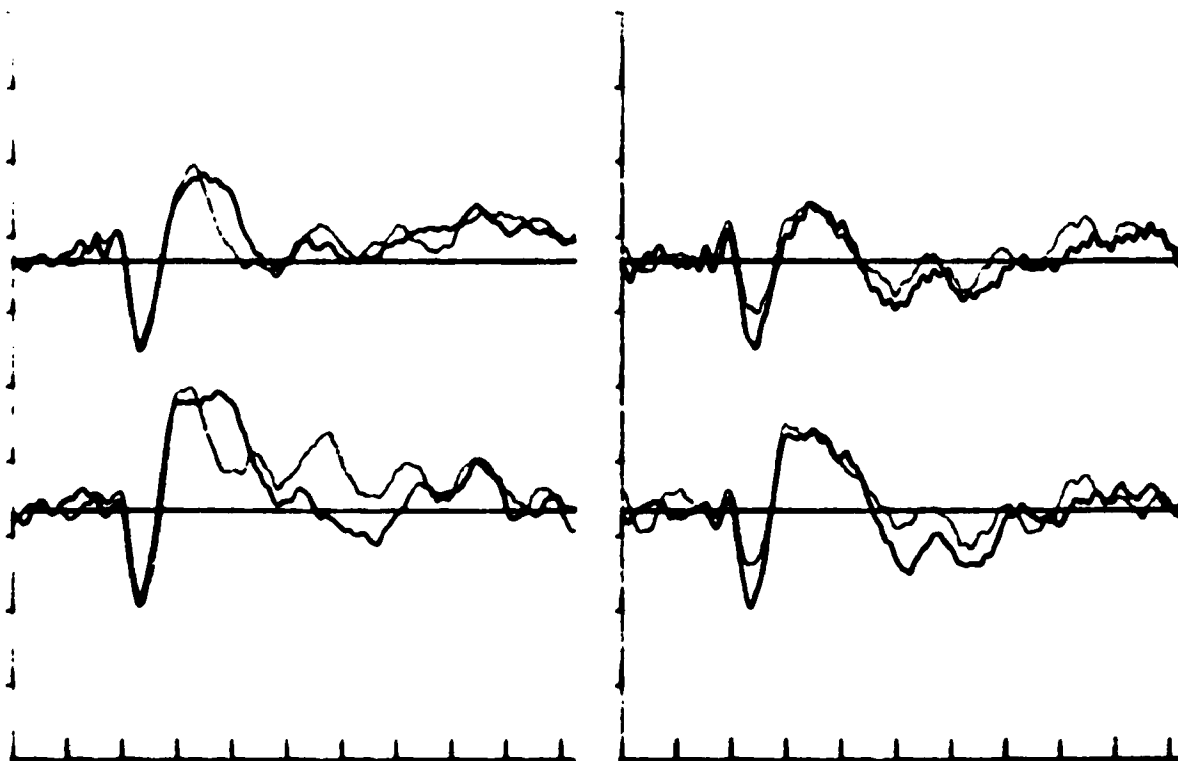
A M



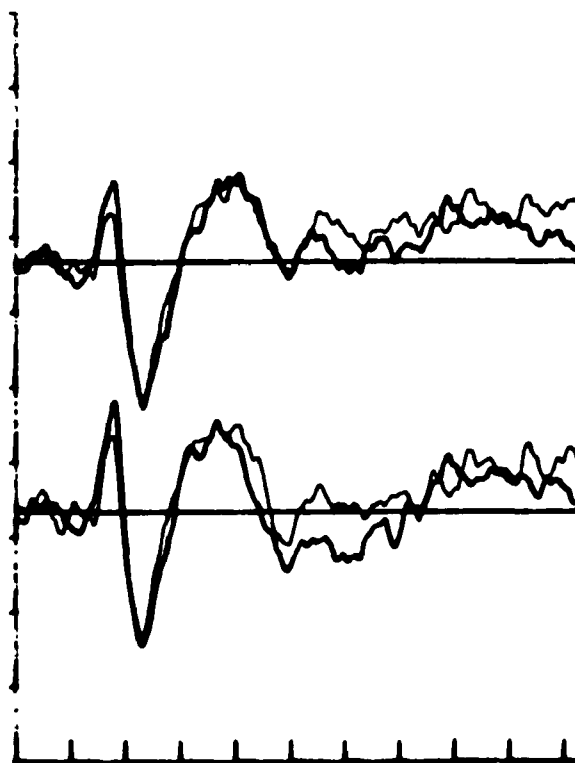
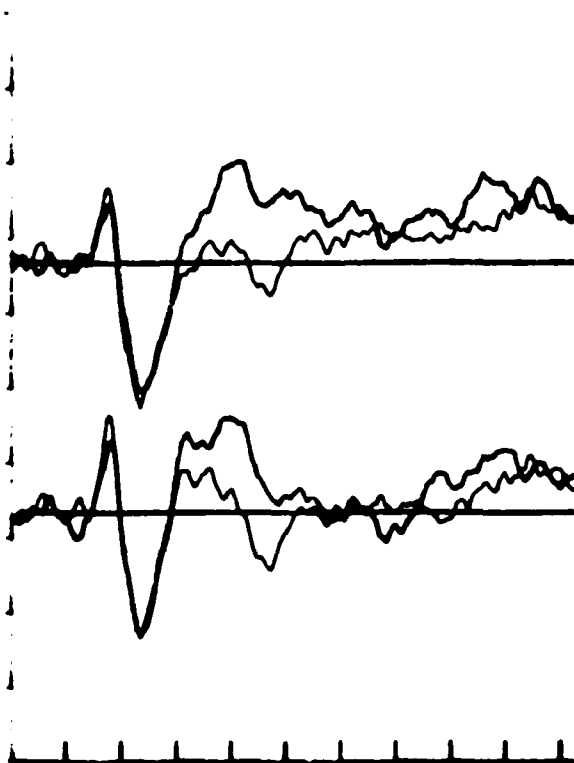
B. a



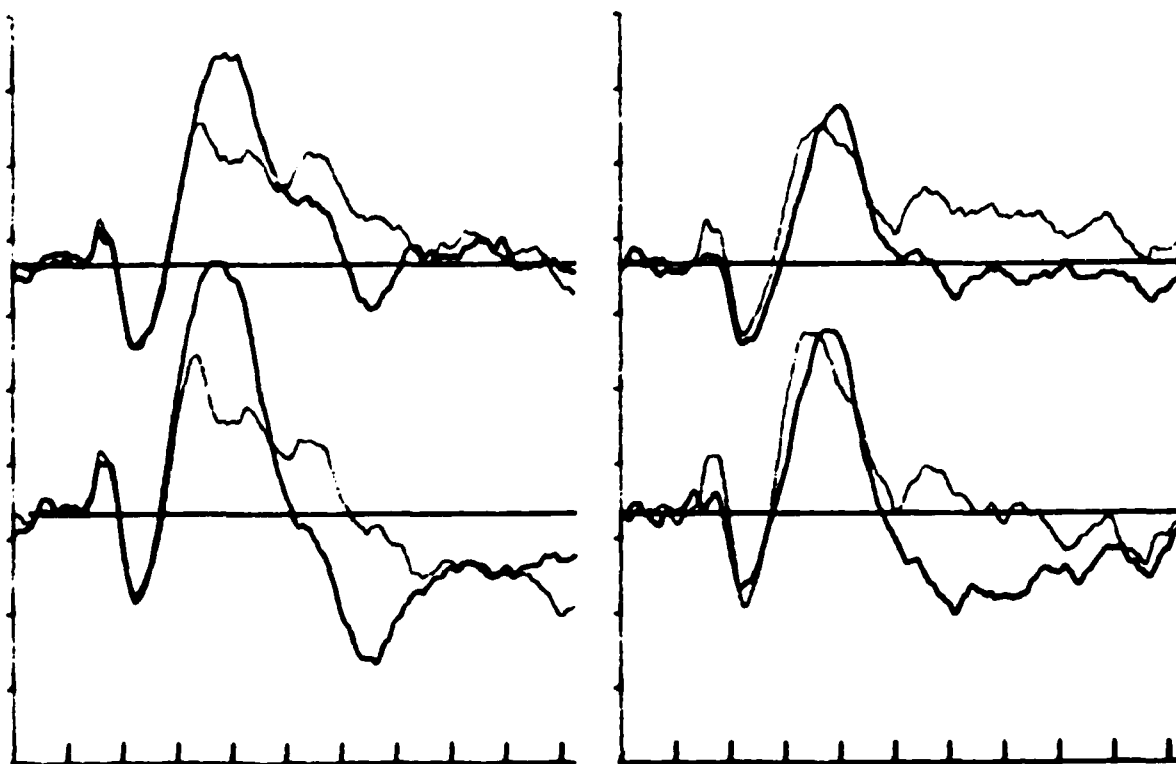
CS



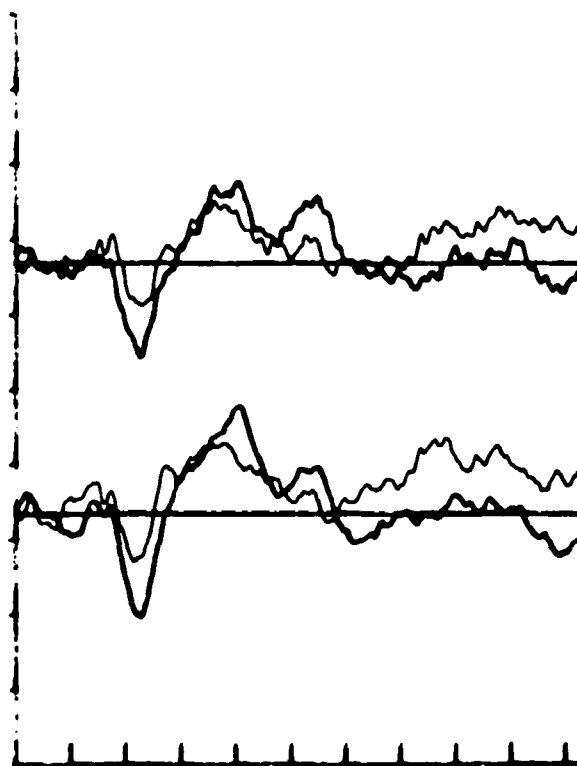
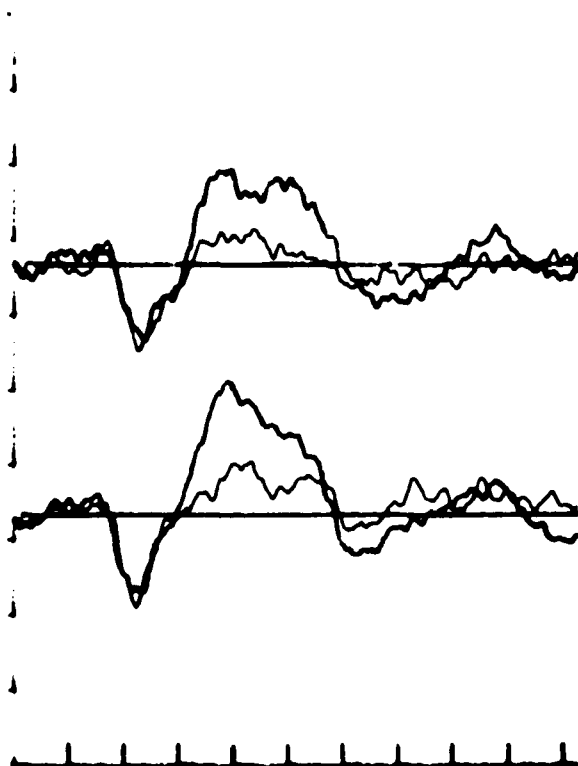
E M



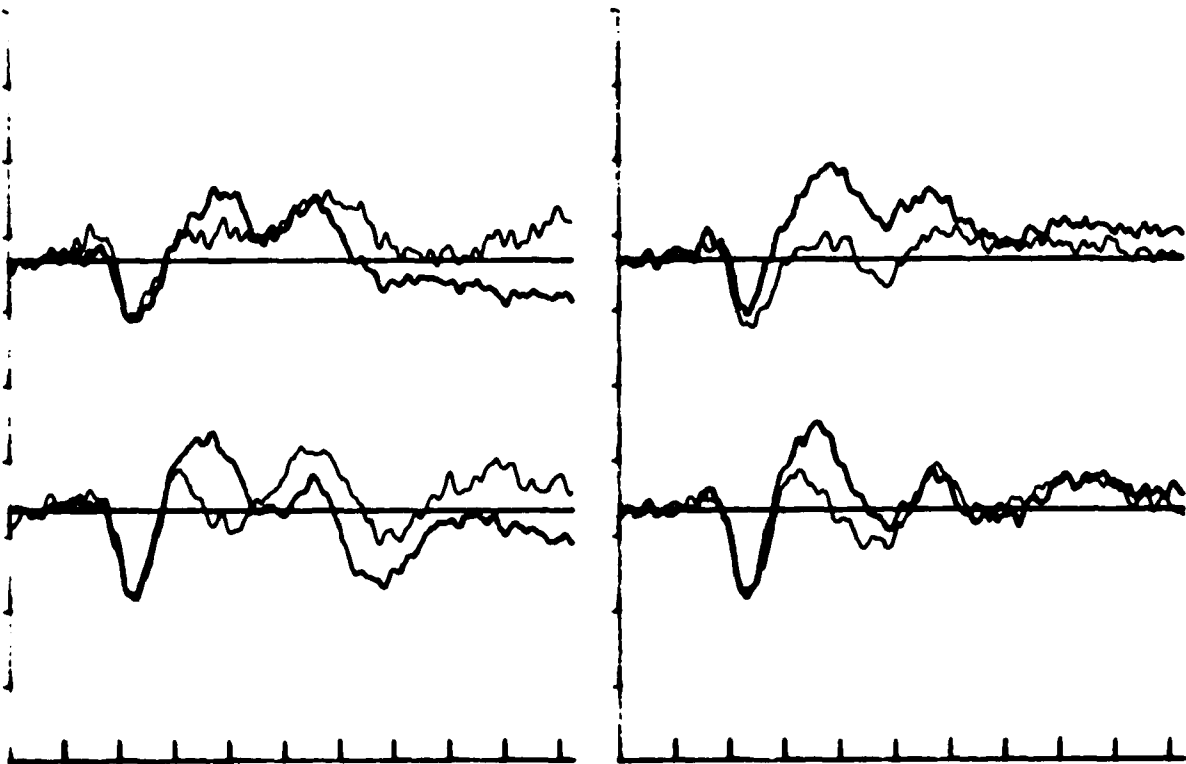
J E



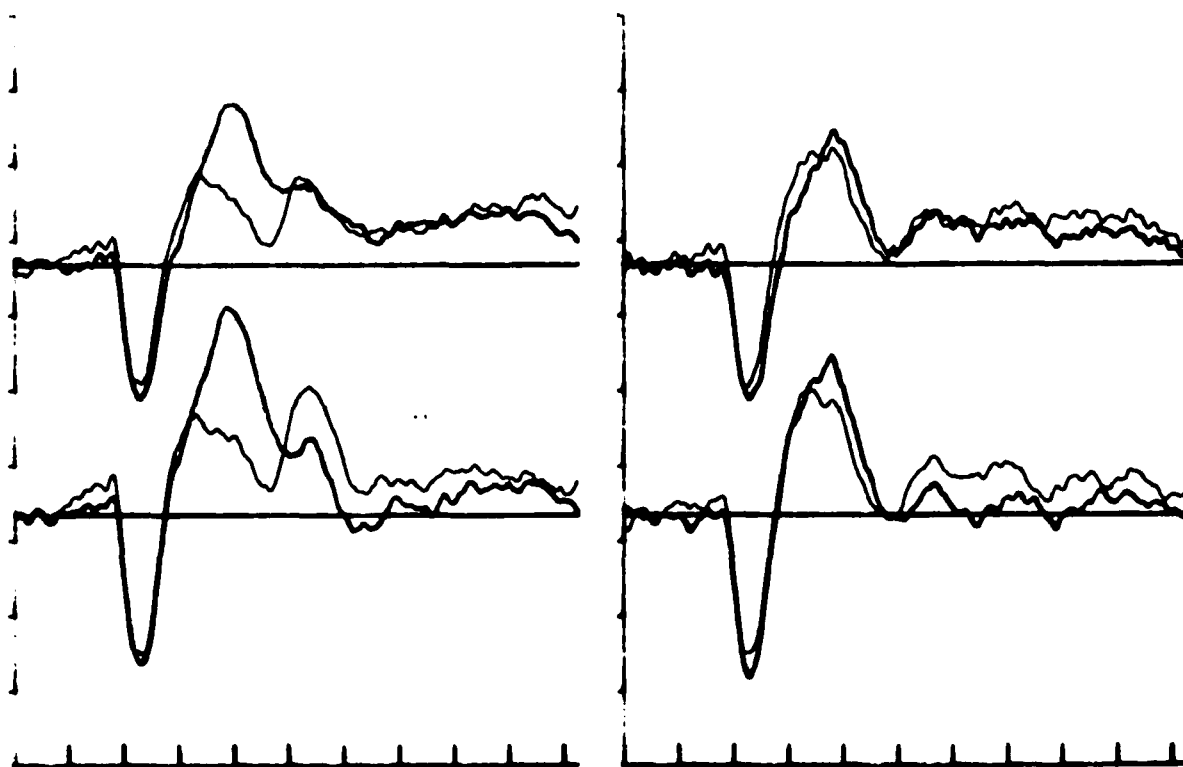
L S



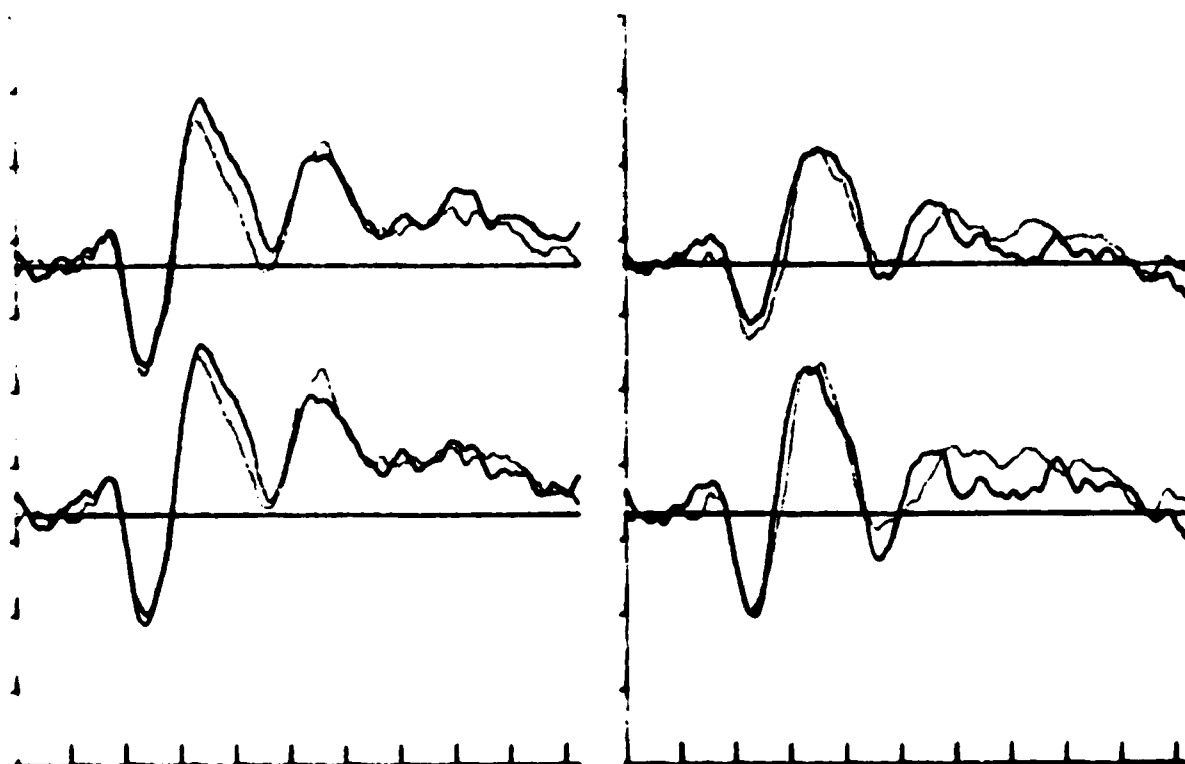
H.8



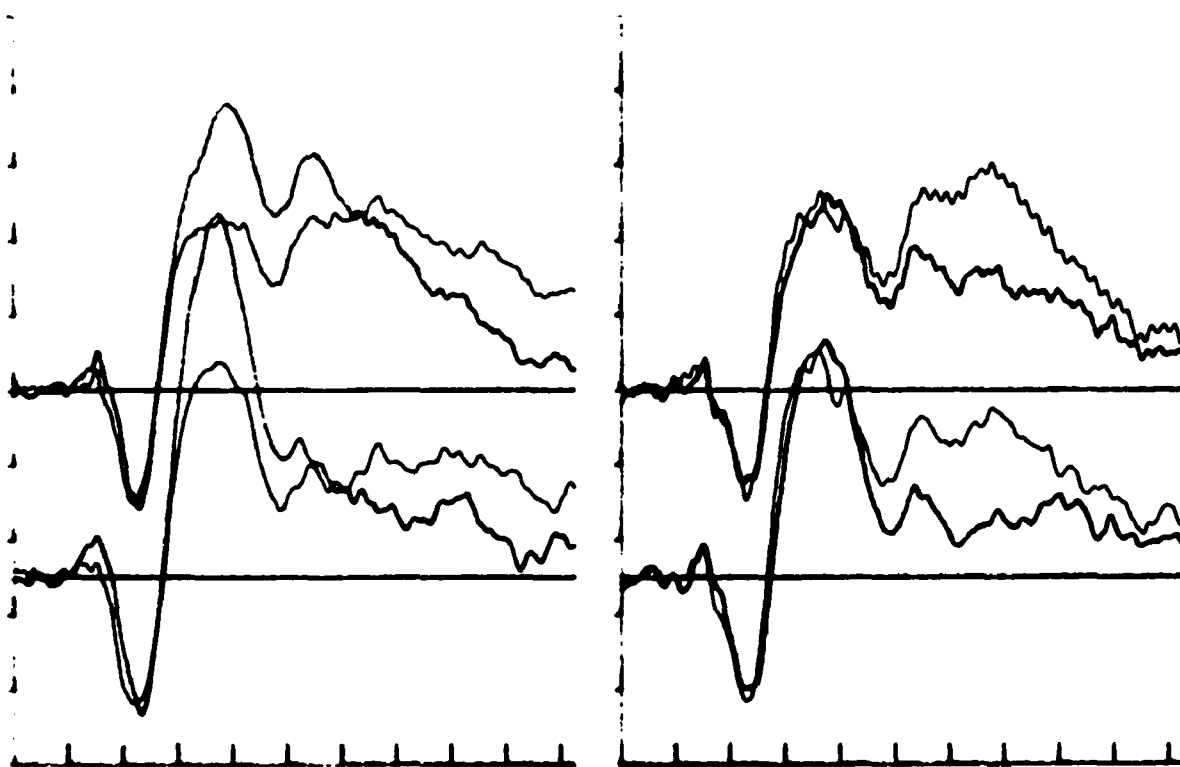
2.8



R R



S H



REFERENCES

- Aine, C. & Harter, M.R., 1984. Hemispheric differences in event-related potentials to Stroop stimuli. Brain and Information: Event-Related Potentials, (R. Karrer, J. Cohen & P. Tueting, eds.) Annals of the New York Academy of Sciences, v. 425, 154-56.
- Allport, D.A., Tipper, S.P. & Chmiel, N.R.J., 1985. Perceptual integration and postcategorical filtering. In M. Posner and O. Marin (Eds.) Attention and Performance XI, Erlbaum, New Jersey, 107-132.
- Anderson, J.R., 1983. The architecture of cognition. Cambridge, Mass., Harvard University Press.
- Bauer, H. & Nirnberger, G., 1981. Concept identification as a function of preceding negative or positive shifts in slow brain potentials. Psychophysiology, 18, 466-69.
- Baribeau-Braun, J., Picton, T., & Gosselin, J., 1983, Feb. 18. Schizophrenia: A neurophysiological evaluation of abnormal information processing. Science, 219.
- Broadbent, D.E., 1958. Perception and Communication. London, Pergamon Press
- Broadbent, D.E., 1970. Stimulus set and response set: Two kinds of selective attention. In D.I. Mostofsky (Ed.) Attention: Contemporary Theory and Analysis, New York, Appleton, Century, Crofts.
- Broadbent, D.E., 1982. Task combination and the selective intake of information. Acta Psychologica, 50, 253-90.
- Bushnell, M.C., Goldberg, M.E. & Robinson, D.L., 1981. Behavioral enhancement of visual responses in monkey cerebral cortex. I. Modulation in posterior parietal cortex related to selective visual attention. Journal of Neurophysiology, 46, 755.
- Butler, R.A., 1968. Effect of changes in stimulus frequency and intensity on habituation of the human vertex potential. The Journal of the Acoustical Society of America, 44, 945-50.

- Cohen, N.J., 1985. Different memory systems underlying acquisition of procedural and declarative knowledge. In D.S Olton, E. Gamzu and S. Corkin (Eds.) Memory Dysfunctions: An Integration of Animal and Human Research from Preclinical and Clinical Perspectives, Annals of the New York Academy of Sciences, V. 444, 54-71.
- Cowey, A., 1985. Aspects of cortical organization related to selective attention and selective impairments of visual perception: A tutorial review. In M. Posner and O. Marin (Eds.) Attention and Performance XI, Erlbaum, New Jersey, 41-62.
- Curry, S.H., Cooper, R., McCallum, W.C., Pocock, P.V., Papakostopoulos, D., Skidmore, S. & Newton, P., 1983. The principle components of auditory target detection. In A.W.K. Gaillard and W. Ritter (Eds.) Tutorials in event related potentials: Endogenous components, Amsterdam: North Holland, 79-117.
- Davis, H., Mast, T., Yoshie, N., & Zerlin, S., 1966. The slow response of the human cortex to auditory stimuli. Electroencephalography and Clinical Neurophysiology, 21, 105-13.
- Deeke, L., Bashore, T. et al., 1984. Movement associated potentials and motor control: Report of the EPIC VI Motor Panel. Brain and Information: Event-Related Potentials, (R. Karrer, J. Cohen & P. Tueting, eds.) Annals of the New York Academy of Sciences, v. 425, 398-428.
- Deeke, L., Heise, B. et al., 1984. Brain potentials associated with voluntary manual tracking: Bereitschaftspotential, conditioned premotion positivity, directed action potential and relaxation potential. Brain and Information: Event-Related Potentials, (R. Karrer, J. Cohen & P. Tueting, eds.) Annals of the New York Academy of Sciences, v. 425, 450-64.
- Desmedt, J. E., & Debecker, J., 1979. Wave form and neural mechanism of the decision P350 elicited without pre-stimulus CNV of readiness potential in random sequences of near-threshold auditory clicks and finger stimuli. Electroencephalography and Clinical Neurophysiology, 47, 648-70.

- Desmedt, J. E., & Debecker, J., 1979. Slow potential shifts and decision P350 interactions in tasks with random sequences of near-threshold clicks and finger stimuli delivered at regular intervals. Electroencephalography and Clinical Neurophysiology, 47, 671-79.
- Desmedt, J. E. & Robertson, D., 1977. Differential enhancement of early and late components of the cerebral somatosensory evoked potential during forced-paced cognitive tasks in man. Journal of Physiology (London), 271.
- Desmedt, J. E., Robertson, D., Brunko E., & Debecker, J., 1977. Somatosensory decision tasks in man: Early and late components of the cerebral potentials evoked by stimulation of different fingers in random sequence. Electroencephalography and Clinical Neurophysiology, 70.
- Deutsch, J.A. & Deutsch, D., 1963. Attention: Some theoretical considerations. Psych Rev., 70, 80-90.
- Donald, M. W. & Little, R., 1981. The analysis of stimulus probability inside and outside the focus of attention, as reflected by the auditory N1 and P3 components. Canadian Journal of Psychology, 35.
- Donald, M. W. & Young, M. J., 1980. Habituation and rate decrements in the auditory vertex potential during selective listening. In H.H. Kornhuber & L. Deecke (Eds.) Motivation, motor and sensory processes of the brain: Electrical potentials, behavior and clinical use. Progress in brain research, v 54, Amsterdam, Elsevier.
- Donchin, E. & Heffley, E., 1979. Multivariate analysis of of event-related potential data: A tutorial review. In D. A. Otto (Ed.) Multidisciplinary perspectives in event-related brain potential research, Washington, D.C., Environmental Protection Agency, EPA-600/9-77-043.
- Douglas, R.M. & Goddard, G.V., 1975. Long-term potentiation of the perforant path-granule cell synapse in the rat hippocampus. Brain Research, 86, 205-215.
- Duncan-Johnson, C. & Donchin, E., 1982. The P300 component of the event-related potential as an index of information processing. Bio. Psychology, 14.

- Duncan-Johnson, C. & Donchin, E., 1979. The time constant in P300 recording. Psychophysiology, 16, 1, 53-5.
- Estes, W., 1984. Global and local control of choice behavior by cyclically varying outcome probabilities. J. of Exp. Psych: Learning, Memory and Cognition, 2, 258-270.
- Fitzgerald P.G. & Picton T.W., May, 1983. Event-related potentials recorded during the discrimination of improbable stimuli. Bio. Psychology, 15.
- Fitzgerald, P.G. & Picton, T.W., 1984. The effect of probability and discriminability on the evoked potentials to unpredictable stimuli. In Brain and Information: Event-Related Potentials, (R. Karrer, J. Cohen & P. Tueting, eds.) Annals of the New York Academy of Sciences, v. 425, 199-203.
- Ford, J., Duncan-Johnson, C., Pfefferbaum, A., & Kopell, B., 1982. Expectancy for events in old age: Stimulus sequence affects on P300 and reaction time. J. of Gerontology, 37, 6.
- Ford, J., Pfefferbaum, A., & Kopell, B., 1982. Effects of Perceptual and cognitive difficulty on P300 and RT in young and old adults. Electroencephalography and Clinical Neurophysiology, 54.
- Friedman, D., Simson, R., Ritter, W. & Rapin, I., 1975. Cortical evoked potentials elicited by real speech words and human sounds. Electroencephalography and Clinical Neurophysiology, 38, 13-19.
- Friedman, D., Vaughan Jr., H. G. & Erlenmeyer-Kimling, L., 1978. Stimulus and response related components of the LPC in visual discrimination tasks. Electroencephalography and Clinical Neurophysiology, 45.
- Fröhlich, W.D., 1978. Stress, anxiety and the control of attention: A psychophysiological approach. In Stress and anxiety (Vol. 5), C.D. Spielberger and I.G. Sarason (Eds.), Wiley, Washington D.C., 99-130.
- Fuster, J.M., 1973. Unit activity in prefrontal cortex during delayed response-performance: neural correlates of transient memory. J. Neurophysiol., 36, 61-78.
- Gaillard, A.W.K. & Verduin, C.J., 1985. Comparisons across paradigms: An ERP study. In M. Posner and O. Marin (Eds.) Attention and Performance XI, Erlbaum, New Jersey, 375-90.

- Gould, L.R. & Goodwin, K.S., 1970. Development and choice behavior in probabilistic and problem solving tasks. Advances in Child Behavior and Development, 5, 214-254.
- Grossberg, S., 1980. How does the brain build a cognitive code? Psych. Rev., 87.
- Halgren, E., et al, 1980. Endogenous potentials generated in the human hippocampal formation and amygdala by infrequent events. Science, 210.
- Hafter, E.R., & Buell, T.N., 1985. The importance of transients for maintaining the separation of signals in auditory space. In M. Posner and O. Marin (Eds.) Attention and Performance XI, Erlbaum, New Jersey, 63-84.
- Hansen, J.C., & Hillyard, S.A., 1980. Endogenous brain potentials associated with selective auditory attention. Electroencephalography and Clinical Neurophysiology, 49.
- Hansen, J.C., & Hillyard, S.A., 1983. Selective attention to multidimensional auditory stimuli. J. of Exp. Psych: Human Perc. & Perf., 9, 1, 1-19.
- Harter, M.R., Aine, C. & Schroeder, C., 1984. Hemispheric differences in event-related potential measures of selective attention. In R. Karrer, J. Cohen, & P. Tueting (Eds.), Brain and Information: Event-Related Potentials. Annals of the New York Academy of Sciences, 425, 210-11.
- Harter, M.R., & Guido, W., 1980. Attention to pattern orientation: Negative cortical potentials, reaction time and the selection process. Electroencephalography and Clinical Neurophysiology, 49.
- Harter, M.R., & Previc, F.H., 1978. Size-specific information channels and selective attention: Visual evoked potential and behavioral measures. Electroencephalography and Clinical Neurophysiology, 45.
- Hashimoto, I., Ishiyama, Y., Yoshimoto, T. & Nemoto, S., 1981. Brainstem auditory evoked potentials recorded directly from human brainstem and thalamus. Brain, 104, 841-59.

- Hebb, D.O., 1949. The Organization of Behavior. New York, Wiley.
- Heron, W., 1957, Jan. The pathology of boredom. Scientific American.
- Hillyard, S. A., 1973. The CNV and human behavior. Electroencephalography and Clinical Neurophysiology, Suppl. 33, 161-71.
- Hillyard, S. A., Hink, R. F., Schwent, V. L. & Picton, T. W., 1973. Electrical signs of selective attention in the human brain. Science, 182.
- Hillyard, S. A., & Munte, T.F., 1984. Selective attention to color and locational cues: An analysis with event-related brain potentials. Perception and Psychophysics, 36, 185-98.
- Hillyard, S. A., Munte, T.F., & Neville, H.J., 1985. Visual-spatial attention, orienting and brain physiology. In M. Posner and O. Marin (Eds.) Attention and Performance XI, Erlbaum, New Jersey, 63-84.
- Hink, R.F., Van Voorhis, S.T. & Hillyard S.A., 1977. The division of attention and the human auditory evoked potential. Neuropsychologia, 15, 597-605.
- Hoffman, J.E. & McMillan, J.W., 1985. Is semantic priming automatic? In M. Posner and O. Marin (Eds.) Attention and Performance XI, Erlbaum, New Jersey, 585-599.
- Hubel, D.H. & Wiesel, T.N., 1962. Receptive fields, binocular interaction and functional architecture in the cat's visual cortex. Journal of Physiology, 160, 106-154.
- Hymovitch, B., 1952. The effects of experiential variations on problem-solving in the rat. Journal of Comparative and Physiological Psychology, 45, 313-21.
- James, W., 1890. Principles of Psychology. New York, Holt.
- Jasper, H., 1958. The 10 20 electrode system of the International Federation (Appendix to report of the committee on methods of clinical examination in electroencephalography). Electroencephalography and Clinical Neurophysiology, 10, 371-75.

- Jennings, J.R. & Wood, C.C., 1976. The c-adjustment procedure for repeated measures analysis of variance. Psychophysiology, 13, 277-78.
- Jewett, D.L. & Williston, J.S., 1971. Auditory evoked far fields averaged from the scalps of humans. Brain, 94, 681-96.
- Johnson, R. & Donchin, E., 1978. On how P300 amplitude varies with the utility of the eliciting stimuli. Electroencephalography and Clinical Neurophysiology, 44.
- Johnson, R. Jr. & Donchin, E., 1980. P300 and stimulus categorization: Two plus one is not so different from one plus one. Psychophysiology, 17, 2, 167-178.
- Johnson, R. Jr. & Donchin, E., 1982. Sequential dependencies and decision making in a changing environment: An electrophysiological approach. Psychophysiology, 19, 183-200.
- Johnston, W.A. & Dark, V.J., 1982. In defense of intraperceptual theories of attention. J. of Exp. Psych: Human Perc. & Perf., 8, 3, 407-21.
- Kahneman, D., 1973. Attention and Effort, Englewood Cliffs, New Jersey, Prentice-Hall.
- Karlin, L., 1970. Cognition, preparation, and sensory evoked potentials. Psych. Bull., 73.
- Klorman, R., et al, 1979. Effects of methylphenidate on hyperactive children's evoked responses during passive and active attention. Psychophysiol., 16, 1.
- Kutas, M., 1984. Subcomponents of the contingent negative variation. In E. Donchin (Ed.), Cognitive Psychophysiology: Event-Related Potentials and the Study of Cognition. Erlbaum, Hillsdale, New Jersey, 191-201.
- Kutas, M., & Hillyard, S. A., 1980. Reading senseless sentences: Brain potentials reflect semantic incongruity. Science, 207, 203-5.
- Kutas, M., & Hillyard, S. A., 1984. Event-related brain potentials elicited by novel stimuli during sentence processing. In R. Karrer, J. Cohen, & P. Tueting (Eds.), Brain and Information: Event-Related Potentials. Annals of the New York Academy of Sciences, 425, 236-41.

- La Berge, D., Van Gelder, P. & Yellot, J., 1970. A cueing technique in choice reaction time. Perception and Psychophysics, 7, 57-62.
- Larkin, W., & Greenberg, G.Z., 1970. Selective attention in uncertain frequency detection. Perception and Psychophysics, 8, 179-83.
- Lennie, P., 1980. Parallel visual pathways: A review. Vision Research, 20, 561-94.
- Loiselle, D. L., et al, 1980. Evoked potential and behavioral signs of attentive dysfunction in hyperactive boys, Psychophysiol., 17, 2.
- Loveless, N., 1979. Event related slow potentials of the brain as expressions of orienting function. In H. D. Kimmel, E. H. Van Olst & J. Orlebeke (Eds.) The Orienting Reflex in Humans. Hillsdale, N. J., Erlbaum.
- Lovrich, D., & Stamm, J., 1983. Event related potentials and behavioral correlates of attention in reading retardation. J. of Clinical Neuropsychology, 5, 1.
- Lucas, J., 1981. The role of efferent inhibition in human auditory attention: An examination of the auditory brainstem potentials. International J. Neuroscience, 12, 137-45.
- Luria, A. R., 1980. Higher Cortical Functions in Man. Basic Books, New York.
- Lynch, J.C., Mountcastle, V.B., Talbot, W.H. & Yin, T.C.T., 1977. Parietal lobe mechanisms for directed visual attention. Journal of Neurophysiology, 40, 362.
- Mattis, S., 1982. Presentation to Experimental Cognition Ph.D. subprogram at The City College of New York, New York.
- McCallum, W.C. & Cummins, B., 1973. The effects of brain lesions on the contingent negative variation in neurosurgical patients. Electroencephalography and Clinical Neurophysiology, 35, 449-56.
- McCallum, W.C. & Curry, S.H., 1984. A comparison of early event related potentials in two target detection tasks. In R. Karrer, J. Cohen, & P. Tueting (Eds.), Brain and Information: Event-Related Potentials. Annals of the New York Academy of Sciences, 425, 242-49.

- McCarthy, G. & Donchin, E., 1976. The effects of temporal and event uncertainty in determining the waveforms of the auditory event related potential (ERP). Psychophysiol. 13.
- McCarthy, G. & Donchin, E., 1981. A metric for thought: A comparison of P300 latency and reaction time, Science, 211.
- McCarthy, G. & Wood, C.C., 1985. Scalp distributions of event related potentials: An ambiguity associated with analysis of variance models. Electroencephalography and Clinical Neurophysiology, 62, 203-208.
- Moran, J. & Desimone, R., 1985. Selective attention gates visual processing in the extrastriate cortex. Science, 229, Aug 23, 782-84.
- Musso, M. F. & Harter, M. R., 1978. Contingent negative variation, evoked potentials, and psychophysical measures of selective attention in children with learning disabilities. In D. A. Otto (Ed.) Multidisciplinary perspectives in event-related brain potential research. Washington, D.C., Environmental Protection Agency.
- Näätänen, R., 1975. Selective attention and evoked potentials in humans-A critical review. Bio. Psychology, 2.
- Näätänen R., 1982. Processing negativity: Evoked-potential reflection of selective attention. Psychological Bulletin, 92, 605-640.
- Näätänen R. Gaillard A., & Mäntysalo S., 1978. The N1 effect of selective attention reinterpreted. Acta Psychologica, 42, 313-329.
- Näätänen R., Gaillard A., & Vares C.A., 1981. Early attention effects on evoked potential as a function of interstimulus interval. Bio. Psychology, 13.
- Näätänen R., Simpson, M. & Loveless, N.E., 1982. Stimulus deviance and evoked potentials. Bio. Psychology, 14, 53-98.
- Niemi, P. & Keskinen, E., 1980. Visual stimulus intensity and location probability: Interactive effects on choice reaction time. Scand. J. Psychol. 21, 175-84.
- Norman, D.A., 1968. Toward a theory of memory and attention. Psych Rev. 75, 522-36.

- Norman, D.A., 1984. Theories and models in cognitive psychology. In E. Donchin (Ed.), Cognitive Psychophysiology: Event-Related Potentials and the Study of Cognition. Erlbaum, Hillsdale, New Jersey, 119-138.
- Okita, T., 1981. Slow negative shifts of the human event-related potential associated with selective information processing. Bio. Psychology, 12.
- Parasuraman, R., 1980. Effects of information processing demands on slow negative shift latencies and N100 amplitude in selective and divided attention. Bio. Psychology, 11.
- Parasuraman, R., 1985. Sustained attention: A multifactorial approach. In M. Posner and O. Marin (Eds.) Attention and Performance XI, Erlbaum, New Jersey, 493-512.
- Peters, J. F., Billinger, T. W. & Knott, J. R., 1977. Event-related potentials of the brain (CNV and P300) in a paired associate learning paradigm. Psychophysiol., 14.
- Picton, T.W. & Hillyard, S.A., 1974. Human auditory evoked Potentials II. Effects of attention. Electroencephalography and Clinical Neurophysiology, 36, 191-99.
- Picton, T.W., Hillyard, S.A., Krausz, H.I. & Galambos, R., 1974. Human auditory evoked Potentials I. Evaluation of Components. Electroencephalography and Clinical Neurophysiology, 36, 179-90.
- Picton, T.W., & Stuss, D.T., 1980. The component structure of the human event related potentials. In H. H. Kornhuber & L. Deecke (Eds.) Motivation, Motor and Sensory Processes of the Brain. Electrical Potentials. Behavior and Clinical Use. Amsterdam, Elsevier.
- Polich, J.M. & Starr, A., 1983. Middle, late and long-latency auditory evoked potentials. In E.J. Moore (Ed.) Bases of Auditory Brainstem Evoked Responses. New York, Grune & Stratton, 345-61.
- Posner, M.I., 1978. Chronometric Explorations of Mind. Hillsdale, N.J., Erlbaum.
- Posner, M.I., 1983. A framework for relating cognitive to neural systems. Delivered as an invited address to EPIC VII in Florence, Italy.

- Posner, M.I. & Snyder, C.R., 1975. Facilitation and inhibition in the processing of signals. In P.M.A. Rabbitt & S. Dornic (Eds.) Attention & Performance V, New York, Academic Press, 669-82.
- Pribram, K. H., 1959. The intrinsic systems of the forebrain. In Handbook of Physiology, McGraw Hill, New York.
- Pribram, K. H., 1961. A further analysis of the behavior deficit that follows injury to the primate frontal cortex. J. Exp. Neurol., 3.
- Pribram, K. H., 1969. Some dimensions of remembering: Steps toward a neuropsychological model of memory. In Perception and Action, K. H. Pribram (Ed.), Penguin Books.
- Pribram, K. H. & Luria, A. R. (Eds.) 1973. Psychophysiology of the Frontal Lobes. Academic Press, New York.
- Pribram, K. H. & Mishkin, M., 1956. Analysis of the effects of frontal lesions in monkeys III. J. Comp. & Physiol. Psychol., 49.
- Pribram, K. H. & McGuinness, D., 1975. Arousal, activation and effort in the control of attention. Psych. Rev., 82.
- Pritchard, R.M., Heron, W. & Hebb, D.O., 1960. Visual perception approached by the method of stabilized images. Canadian Journal of Psychology, 14, 66-77.
- Pritchard, W.S., 1981. Psychophysiology of P300. Psych. Bull., 89, 3.
- Proteau, L. & Alain, C., June 1983. Strategie de decision en fonction de l'incertitude de l'evenement: 1. Latence de la decision. Canadian Journal of Applied Sport Sciences, 8, 2, 63-71.
- Proteau, L. & Laurencelle, L., June 1983. [Decision strategies: Effect of the probability of events and times depending on choice RT and movement time.] Canadian Journal of Applied Sport Sciences, 8, 2, 54-62.
- Ritter, W. et al., 1984. Cognition and event-related potentials: I. The relation of negative potentials and cognitive processes. In R. Karrer, J. Cohen, & P. Tueting (Eds.), Brain and Information: Event-Related Potentials. Annals of the New York Academy of Sciences, 425, 24-38.

- Ritter, W., Rotkin, L. & Vaughan, H.G., 1980. The modality specificity of the slow negative wave. Psychophysiology, 17, 222-27.
- Ritter, W., Simson, R. & Vaughan, H.G. Jr., 1972. Auditory cortex potentials and reaction time in auditory discrimination. Electroencephalography and Clinical Neurophysiology, 33, 547-555.
- Ritter, W., Simson, R., Vaughan, H.G. Jr. & Friedman, D., 1979. A brain event relating to the making of a sensory discrimination. Science, 203, 1358-61.
- Ritter, W., Vaughan, H. G. Jr. & Costa, L. D., 1968. Orienting and habituation to auditory stimuli: A study of short term changes in averaged evoked responses. Electroencephalography and Clinical Neurophysiology, 25.
- Ritter, W., Vaughan, H.G. Jr. & Simson, R., 1983. On relating event-related potential components to stages of information processing. In A.W.K. Gaillard and W. Ritter (Eds.), Tutorials in ERP Research: Endogenous Components, North Holland Publishing Co.
- Rockstroh, Elbert, Birnbaumer & Lutzenberger 1982. Slow brain potentials and behavior Baltimore: Urban & Schwarzenberg.
- Roland, P.E., 1981. Somatotopical tuning of postcentral gyrus during focal attention in man. A regional cerebral blood flow study. J. of Neurophysiol., 46, 744-754.
- Roland, P.E., 1982. Cortical regulation of selective attention in man. A regional cerebral blood flow study. J. of Neurophysiol., 48, 1059-77.
- Ruchkin, D.S. & Sutton, S., 1978. Equivocation and P300 amplitude. In D. A. Otto (Ed.) Multidisciplinary perspectives in event-related brain potential research, Washington, D.C., Environmental Protection Agency, EPA-600/9-77-043.
- Ruchkin, D.S., Sutton, S. & Stega, M., 1980. Emitted P300 and slow wave event-related potentials in guessing and detection tasks. Electroencephalography and Clinical Neurophysiology, 49.
- Sams, M., Alho, K. & Näätänen, R., 1983. Sequential effects on the ERP in discriminating two stimuli. Bio. Psych., 17, 41-58.

- Sanquist, T.F., Rohrbaugh, J.W., Syndulko, K. & Lindsley, D.B., 1980. Electrocortical signs of levels of processing: Perceptual analysis and recognition memory. Psychophysiol. 17.
- Savi, D. & Julesz, B., 1985. "Where" and "what" in vision. Science, June 7, 1217-1219.
- Schacter, D.L., 1985. Priming of old and new knowledge in amnesic patients and normal subjects. In D.S. Olton, E. Gamzu and S. Corkin (Eds.), Memory Dysfunctions: An Integration of Animal and Human Research from Preclinical and Clinical Perspectives, Annals of the New York Academy of Sciences, V. 444, 41-53.
- Schiffman, R.M. & Schneider, W., 1977. Controlled and automatic information processing: II. Perceptual learning, automatic attending and a general theory. Psychological Review, 84, 127-189.
- Schwent, V.L., Snyder, E. & Hillyard, S.A., 1976. Auditory evoked potentials during multichannel selective listening: Role of pitch and localization cues. J. Exp. Psych: Human Perception & Perf. 2.
- Skinner, J.E. & Yingling, C.D., 1977. Central gating mechanisms that regulate event-related potentials and behavior. A neural model for attention. In J.E. Desmedt (Ed.), Progress in Clinical Neurophysiology, Vol. 1, Karger, Basel, 28-68.
- Snyder, E., Hillyard, S., & Galambos, R., 1980. Similarities and differences among the P3 waves to detected signals in three modalities. Psychophysiol. 17, 2.
- Squires, N.K., Squires, K.C. & Hillyard, S.A., 1975. Two varieties of long-latency positive waves evoked by unpredictable auditory stimuli in man, Electroencephalography and Clinical Neurophysiology, 38.
- Squires, K.C., Wickens, C., Squires, N.K. & Donchin, E., 1976. The effect of stimulus sequence on the waveform of the cortical event related potential. Science, 193, 1142-46.
- Stockard, J.J., Stockard, J.E. & Sharbrough, S.W., 1977. Detection and localization of occult lesions with brain stem auditory responses. Mayo Clinic Proceedings 52, 761-69.

- Sutton, S. & Ruchkin, D.S., 1984. The late positive complex: Advances and new problems. Brain and Information: Event-Related Potentials, (R. Karrer, J. Cohen & P. Tueting, eds.) Annals of the New York Academy of Sciences, v. 425, 1-23.
- Syndulko, K. & Lindsley, D.B., 1977. Motor and sensory determinants of cortical slow potential shifts in man. In J.E. Desmedt (Ed.), Progress in Clinical Neurophysiology, Vol. 1, Karger, Basel, 97-131.
- Teece, J.J., Savignano-Bowman, J. & Dessonville, C.L., 1984. CNV and myogenic functions I. Muscle tension produces a dissociation of CNV and EMG. Brain and Information: Event-Related Potentials, (R. Karrer, J. Cohen & P. Tueting, eds.) Annals of the New York Academy of Sciences, v. 425, 283-88.
- Teece, J.J., Cattanach, L., Boehner-Davis, M.B. & Clifford, T.S., 1984. CNV and myogenic functions II. Divided attention produces a double dissociation of CNV and EMG. Brain and Information: Event-Related Potentials, (R. Karrer, J. Cohen & P. Tueting, eds.) Annals of the New York Academy of Sciences, v. 425, 289-94.
- Thatcher, R.W., 1977. Evoked-potential correlates of delayed letter matching. Behav. Bio. 19.
- Thompson, W.R. & Heron, W., 1954. The effects of restricting experience on the problem-solving capacity of dogs. Canadian Journal of Psychology, 8, 17-31.
- Treisman, A.M., 1964. Selective attention in man. British Med. Bull. 20, 12-16.
- Tucker, D.M., March 1986. Asymmetries of emotional arousal. Paper presented at Brain and Emotion: The Neuropsychology of Affect, the 7th annual conference of The New York Neuropsychology Group, New York.
- Vaughan H.G. Jr., Ritter W. & Simson R., 1980. Topographic analysis of auditory event-related potentials. In H.H. Kornhuber & L. Deecke (Eds.) Motivation, motor and sensory processes of the brain: Electrical potentials, behavior and clinical use. Progress in brain research, v. 54, Amsterdam, Elsevier.

- Walter, W.G., Cooper, R., Aldridge, V.J., McCallum, W.C. & Winter, A.L., 1964. Contingent negative variation: an electrical sign of sensorimotor association and expectancy in the human brain. Nature, (Lond.) 203, 380-84.
- Wickens, C., Kramer, A., & Donchin, E., 1984. The event-related potential as an index of the processing demands of a complex target acquisition task. In R. Karrer, J. Cohen & P. Tueting (Eds.) Brain and Information: Event-Related Potentials, Annals of the New York Academy of Sciences, v. 425, 295-99.
- Wickens, C., Kramer, A., Vanesse, L., & Donchin, E., 1983, Sept. 9. Performance of concurrent tasks: A psychophysiological analysis of the reciprocity of information-processing resources. Science, 221.
- Wilkinson, R.T. & Lee, M.V., 1972. Auditory evoked potentials and selective attention, Electroencephalography and Clinical Neurophysiology, 33.
- Wood, C.C., McCarthy, G., Squires, N.K., Vaughan, H.G., Woods, D.L. & McCallum, W.C., 1984. Anatomical and physiological substrates of event-related potentials. Brain and Information: Event-Related Potentials, (R. Karrer, J. Cohen & P. Tueting, eds.) Annals of the New York Academy of Sciences, v. 425, 681-721.
- Wood, C.C., McCarthy, G. 1984. Principal components analysis of event-related potentials: Simulation studies demonstrate misallocation of variance, Electroencephalography and Clinical Neurophysiology, 59, 249.
- Wright, A.A., Santiago, H.C. & Sands, S.F., Aug. 1980. Monkey memory: Same/different concept learning, serial probe acquisition, and probe delay effects. J. Exp. Psych. Animal Beh. Proc., 10 (4) 513-29.
- Zubek, J.P., (ed.), 1969. Sensory deprivation: Fifteen years of research. New York, Appleton-Century-Crofts.