CORE
Metadata, citation and similar papers at core.ac.uk
Provided by Illinois Digital Environment for Access to Learning and Scholarship Repository

UNIVERSITY OF ILLINOIS

August 3 1992

THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

Mr. Ian Wickram

ENTITLED A Psychophysiological Investigation of Naatanen's Attentional Trace Hypothesis

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF B.A. in Psychology

Arthur F. Kramer
Instructor in Charge

APPROVED: Arthur F. Kramer

HEAD OF DEPARTMENT OF E. Donchin

O-1364

A Psychophysiological Investigation of Naatanen's Attentional Trace Hypothesis

By

Ian E. Wickram

Thesis

for the

Degree of Bachelor of Science

in

Liberal Arts and Sciences

College of Liberal Arts and Sciences
University of Illinois
Urbana, Illinois

1992

Table of Contents

Introduction

In our perception of the world we do not ordinarily consider the vast amounts of information that is registered at the sensory receptors, only to be neglected later by the bulk of phenomenal awareness. Nor do we tend to question why some stimuli elicit our attention without our effort. Thus in our perceptions of the world we are limited by the confines, and parameters of our ability to focus on certain stimuli through attentional mechanisms in order to bring them into phenomenal awareness, or consciousness. So perhaps it is easy to see why attentional issues are important to many fields of study involving sensation and perception. It can be said of attention and perception that "what you see," is not always all of "what you get." Let us take a closer look at these attentional processes, and mechanisms to understand them more clearly.

We will focus here on first of all describing some of the core concepts, and ideas implicit in models of selective attention. Next we will begin to examine the methodology of event-related potentials (ERPs) to illustrate how cognitive psychophysiology can contribute to our models of selective processes. We will focus on the auditory modality since this is the modality in which I have empirically examined selective processes. Finally having examined the relevant auditory ERP research, we will introduce the central question of this investigation on the relevance of particular psychophysiological correlates to auditory selective attention. We shall start with a discussion of selective attention to make clear how the term is defined and used within the experimental literature.

Attention:

Its General Properties and Metaphors

Let us start with a simple definition offered by Kahneman (1973) which defines selective attention as a process in which an "*organism selectively attends to some stimuli, or aspects of stimuli, in preference to others.*" This process of selection, and its development is what we will be referring to most often as we discuss attention, and its relation to auditory perception. Another aspect of selective attention sometimes emphasized, is its importance in contributing to the overall behavior of the organism by "*facilitating a response.*" (Tecce, 1972.) Thus by selectively attending to relevant stimuli we are able to enhance processing and make use of this enhancement to act more effectively. Another aspect of selective attention often commonly pondered is its relation to phenomena of memory and human consciousness. The very idea that one might process certain stimuli over others brings up, for some, issues over the availability to awareness of both attended, and unattended stimuli after processing. But when we are discussing attention within this work it should be understood that we are talking about phenomena of attention, and not consciousness to which attention appears to be a precursor. Still one of the many appeals of this field is that it comes close to defining what consciousness is, and by what means we are able to understand it.

Some researchers have even gone so far as to say that a organism with the selectivity of attention is precisely what it means to be conscious, such as Posner (1982.) In summation these three initial assumptions of attention, as a selective process that can influence the efficacy of behavior, and the nature of awareness, form the underlying intuitive sense of our use of the term selective attention.

Crucial to our understanding of selection, is the metaphor with which we choose to illustrate it. Perhaps the most well known model of information processing is that of Broadbent (1958), which in rather simple terms attempts to integrate the selective attention, and memory capacity systems. Although in this investigation we will be focussing mainly on the former, there are processes involved in selection which will be seen to interact with phenomena of memory. The traditional view in information processing characterizes selective attention as a filter which operates at some point to channel parrallel processing of input (internal or external) that occurs to provide serial contact with memory storage wherein exists presumably phenomenal awareness. Broadbent's model became the popular basis of the approach to use information processing metaphors in describing cognitive processes like attention. In adapting this metaphor we are lead also to accept both an epistemology and a basic paradigm that suits information processing.

David Marr (1982) delineates an epistemology of information processing devices in three levels of description which we can use both to organize our knowledge and questions on the nature of selective processing. Marr refers to a level of *computational theory,* in which the overall goals and purposes of the processing are revealed. There is also the level of *representation and algorithm,* in which the symbolic way the device accomplishes its goal is explored. Finally there is the level of *implementation and hardware* where one can examine how the goals are accomplished in terms of actual materials. A real understanding is gained when knowledge at all three levels can be integrated although each level is complete in itself as a description. Let us now continue our discussion of selective processes by discussing relevant ideas about attention gained at each level. This should have the effect of familiarizing the reader with the previous findings relevant to this work, and also of providing a complete framework within which to understand it.

There have been many approaches to understanding why selection takes place. Let us look at it in the terms of the computational theory of David Marr, which calls us to look at the overall purposes of selection and the constraints under which it operates. In examining the latter first, we find that selection operates within the physiologically limited information processing capabilities of the human brain. It seems obvious that the need for selection must signal a limitation of this sort on the capacity to process. The limited capacity model has become somewhat of a core concept of attention in defining its constraints. This also leads directly to an explanation of the former question of why selection occurs. Selection as per the limited capacity model, operates in order to keep the information processing systems of an organism from being overloaded. So selection operates to filter out unwanted, or irrelevant stimuli and allow a facilitation of the relevant stimuli to cause a proper response. Thus at the level of computational theory we have some idea of why attention is used within the human information processing system. At this point our line of questioning might lead us to seek out more information as to how selection actually occurs in terms of human information processing.

This question of how selection is accomplished brings us to examine evidence from the level of representation and algorithm. The traditional approach to questions at this level, is to use the chronometric paradigm. Mental chronometry involves the investigation of the time-course of information processing (Posner, 1978). Implicit in this method is the assumption that there are fundamental stages of processing which can be described in terms of their time of onset, and offset following, or preceding the presentation of a stimulus. Furthermore it is assumed that by using behavioral measures of a sensitive enough temporal resolution, such as reaction time in msec, one can come to illuminate these otherwise unobservable mental events. Using the chronometric paradigm one may examine the sort of evidence which reveals the temporal dynamics of processing, and ultimately gain insight into the representation and algorithm involved in selection. Later as we examine the psychophysiological work we shall see that most of the investigation we shall concern ourselves with, will occur mostly at this level. Now we will begin to extend these ideas by asking the question of when selection occurs in information processing. This leads us to examine the debate between early versus late selection.

Early vs Late Selection

The idea that some sort of selection process occurs during our exposure to an environmental setting naturally leads to the question of at what time relative to other information processing events does selection occur. This question brings us to look at selection in terms of a time course analysis of its development and duration. The early selection models postulate selection before any categorization, or recognition of the incoming stimuli, while late selection operates as a result of the categorization, or recognition of the stimuli. The early selection model further emphasizes the role of physical stimulus attributes, (eg: spatial location) in the selection process as being crucial to the criterion of relevancy. This has led to the idea that early selectivity functions like a spotlight in its operation of what stimuli will enter full perception, especially when applied to visual stimuli. Late selection theorists on the other hand suggest that selection occurs on the basis of semantic attributes of stimuli. Allport (1989) sums it up well when he states that, "any operation contingent on spatial/sensory properties or relations is attributed to an early stage of processing; any operation contingent on categorical or other semantic criteria is attributed to a late stage of processing" (p. 635) . Evidence has appeared for both models of selective attention in the literature such as Deutsch and Deutsch (1963) for the late, and Treisman, Squire, and Green (1972) for the early position. This has occurred despite the fact that both of these papers used similar auditory stimulus detection paradigms. Later on when more recent studies involving the methods of cognitive psychophysiology are reviewed the evidence may be seen to favor the early selective process model. Now that we have examined the debate over when selection occurs, let us examine another issue at the level of representation and algorithm regarding the controversy over how selection develops and is maintained. This is the debate over active versus passive selection of stimuli.

Active vs Passive Selection

In this debate over active versus passive selection, the analogy of channels of selective attention will prove useful in explaining the underlying ideas. Channels of selective attention can be thought of in terms of a dichotic listening experiment in which a subject is instructed to listen to stimuli presented to one ear and ignore stimuli that are presented the other ear. Within this framework ears have often been thought of as information channels. In discussing the issue of active versus passive processing we shall find the question of note is whether one can without effort attend to an empty channel (passive selection), or rather if recent exposure to an attended stimulus in the channel is necessary for selection to occur. The passive selection models can be thought of as a filters that once set, can be maintained without taxing the information processing capabilities further. For example in the literature we find Posner, Cohen, Choate, Hockey, and Maylor (1984) describing a passive model of attention as one which, "can be maintained independently of the subject's focus of attention" (p. 50) . Thus they do not need to be the subject of an organisms active awareness, or concentration. In a way the passive models are really independent of the locus of selective attention, and are somewhat pre-attentive.

Active selection models postulate that to the contrary, the filter can not be maintained, or developed without recent sensory exposure to give a memory cue for comparison of all stimuli. Thus the active selection models state that one could not attend to a channel (empty) in advance of receiving stimuli, while the passive models have no such prohibition as long as the process is preset in some way. Schneider, Dumais, and Schiffrin (1984) refer to such processes in terms of being "slow, generally serial, effortful, capacity limited," and "subject-regulated." In the years subsequent to the introduction of this debate there have been a number of reviews of this algorithmic metaphor of active/passive selection which concluded essentially that the distinction was misleading, such as Ryan (1983). But the utility of the metaphor at least as language has tended to propagate the distinction as a functional description of certain aspects of attention.

Now let us move on to examine a few issues of how attention might actually be realized in terms of physiology. As we move to the level of hardware and implementation we begin to examine not only the temporal dynamics of processing but the processor itself. We already know from our computational metaphor of limited capacity, that the processor must be limited in its function of perception, or else we would not have to be looking for an attentional neural substrate. The issue we need to examine is essentially how many neural substrates are we talking about? Shall we naively assert that attention is but one system simply because it has one obvious consequence of selection? Research in the area of Neuropsychology has tended to discourage this conclusion by demonstrating specific deficits of attention arising from different neurological substrates. Also as Cowey (1984) points out, the related connectionist models of the brain would call for a division of the problem of capturing attention physiologically "into small, nearly independent, and specialized subprocesses." So from the strength of these arguments one might be extremely wary of talk of selection as a global system, with similar temporal dynamics for each modality, and for similar processes of selection within each one. When we discuss the ERP literature it perhaps will become more apparent that this is so. Now given these ideas of attention, and the issues considered in relation to the models, let us proceed to review the concepts, and methods of ERP research to appreciate their unique contribution to the understanding of selective processes.

Event-Related Potentials:

Their Utility as Behavioral Measures

Recent advances in technology have given us a plethora of techniques for imaging the human brain to view its information processing activities. In such a way we can come to understand the structures and processes involved in the workings of selective attention in humans, and other organisms. While techniques such as CAT, and PET scans provide very good spatial, and metabolic resolution of the brain as a whole, they do not provide much resolution in the time domain. This limits the usefulness of such technologies in the investigation of brain systems at the level of representation and algorithm. The reason for this is that algorithmic attention research is dependent on the chronometric paradigm. This requires resolution in the time domain which could reveal the neural activity actually developing during a selective attention experiment, and which the majority of the neuroimaging technologies do not currently possess. The method of choice for cognitive psychophysiologists at the present, is to use electroencephalography (EEG), to derive event related brain potentials (ERPs) both because of their superior temporal resolution (in msec), and their relative friendliness in terms of safety, and economical constraints.

EEG is thought to represent the patterns of gross electrical potential of the firings of neurons in the brain measured at the scalp by electrodes. The electrical potential measured is thought to result from activity going on at all levels of the human brain, as the scalp acts as a volume conductor to diffuse activity from one area to another. The reason why ERPs are so useful in the time domain is that the electrical potentials measured can be converted to voltage that varies across msec time intervals. Thus ERPs can provide the same amount of temporal resolution as our normal reaction time measures, but also some limited structural resolution through the measurement of an actual physiological signal, that to differing degrees reflects the processing of external stimuli. We can use this limited structural information about the general summation of neural firing to add on to our knowledge of the unobserved mental processes, which if properly used, can offer some physiological constraints to our algorithmic metaphors. In such a way we can come to understand something about what processes the brain might actually be using to select information from the environment, allthough not too much as to how it is physically accomplished.

All that we need to observe these processes is to present stimuli and tasks requiring a specific process of interest. This is essentially the strength behind what cognitive psychophysiologists have termed event-related potentials (ERPs). In this methodology the idea behind the technique is that patterns of electrical activity in the brain should be fairly predictable, and fall into discernable patterns in response to a repeated stimulus requiring similar processing each time. By averaging a large number of responses, neural activity which is not reflective of the stimulus locked processing should cancel out, since it should not be present in each trial. By experimentally manipulating the types of processing involved in a task we can come to understand the relationship between neuronal activity and human information processing. Ultimately then we can reveal some specific information processing systems, and neurological components in terms of their representation and algorithm.

This is not to say however that an individual neural response should be expected to resemble the global ERP. There can be all kinds of contributions in the individual waveform from processes ongoing in the brain and other structures which do not represent the process of interest. So as stated earlier, it is necessary to separate the contribution of these ongoing processes from the waveform in the stimulus, or event-related contribution, which should be time-locked to the event itself. As long as we have been careful, and used a sufficient number of trials then the event-related neural activity should be dominant in the averaged waveform. This is also not to imply that all processes in the brain should have ERP correlates, as the positioning of the neural generators involved may be such that their activity will not be seen. So researchers present stimuli to the subject and measure the changes in potential as a result of the processing of the stimulus, and try to discern if the potential measured is related to the mental process under investigation. By studying the averaged patterns of potential measured for the regular occurrence of peaks and crests in the waveform researchers can come to discern certain components in the data related to unique stages in information processing of the brain. This is what is meant within this work by the word component following the definition of Donchin et al. (1978) of an ERP as a "source of controlled, observable variability."

Many distinct components have been measured and recorded that are thought to represent different stages in information processing of the brain. Some of these are related to selective attentional processes, and ERP evidence has been used extensively in such studies in the past, and especially now in present day research. It is in part due to the attractiveness of this technique that attention research in general has been revitalized after suffering many years at the hands of behaviorism which found it too mentalistic. As early as Haider, Spong, and Lindsley (1964) in vigilance monitoring experiments researchers found that attended stimuli elicit ERPs with greater amplitudes than unattended stimuli on a vigilance task. As the main concern of the present investigation is with auditory selective processes, the ERPs discussed will all come from that modality. Many of these components are named simply by their average time of onset after a stimulus (latency), and whether they are positive or negative waveforms (polarity). Thus a P300 component is a positive peak occurring around 300 msec after stimulus onset. Referring to components by their polarity, and latency is the most common nominal classification of ERPs. Components are also usually understood by the nature of their relationship to the psychological state of the subject, as with the distinction between endogenous and exogenous components.

Endogenous vs Exogenous Components

The earlier components recorded in an ERP are generally thought to reflect the delivery of the stimuli coded at the receptors to the cortex . These components are said to be exogenous and defined by Hillyard (1986) as, "relatively independent of the psychological state of the subject," and are usually "highly sensitive to both the physical parameters of the eliciting stimuli, and the integrity of the mediating neural structures" (p. 399) . For example there is the No component, which is thought to reflect the arrival point of the stimulus to the cortex. After the stimulus has been delivered in some form to the cortex, components can be found that are thought to more directly involve some of the processes in selective attention. These components are said to be endogenous and reflect as Hillyard (1986) termed, the "state of the subject, the meaning of the stimulus, and the information processing demands of the task" (p. 399) . As the investigations presented here are concerned with the process of selection, the components which are of primary interest are thought to be endogenous. As endogenous components are task sensitive, what components one sees depends on the nature of the specific task being used. Accordingly let us now move our discussion to a description of the relevant previous findings in relating psychophysiological observations to selective processes.

Issues in ERP Research of Selective Processes

The N1 Effect of Selective Attention

One of the first components implicated in being a correlate of selective attention was the N100. It was found that when subjects were instructed to pay attention to particular tones, that the N100 (or N1) was augmented in amplitude for those tones versus the unattended tones. However disagreement in the field occurred when it was shown that the effect disappeared when the inter-stimulus intervals were randomized to reduce subject expectancy (Naatanen, 1967). It was not until Hillyard, Hink, Schwent, and Picton (1973) that a genuine N1 effect was seen by reducing the ISIs considerably. Hillyard used this finding to argue for the early and active algorithmic metaphors of selection. However it was soon to be seen that the N1 effect was not reliable unless the ISIs were as short as those Hillyard had used. Why this should be true began to prove puzzling to researchers, especially coupled with other anomalies like the Donald and Young (1982) finding that the N1 effect emerged gradually during the task after many repetitions of stimuli. Meanwhile Naatanen and Gaillard (1978) had begun to show a slow endogenous selective psychophysiological correlate, they called processing negativity(PN), when using longer ISIs then the Hillyard group. Naatanen hypothesized that the N1 effect the Hillyard group was finding was really an earlier phase of PN found with longer ISIs. Although the Hillyard group (1980,1981) referred to the phenomena differently as the "negative difference" or Nd, they also found the same phenomena as Naatanen. It was then agreed that PN, or Nd was manifested in two components, one which was early which was mistaken as an N1 effect, and the other at a later portion where Naatanen (1978) had studied it. Since then there have been a number of interesting findings which have begun to illuminate how selection is developed and maintained.

The Nd or PN effect of Selective Attention

Hanson and Hillyard (1983) explored the sensitivity of the Nd to the selection of multidimensional stimuli with the features of frequency (pitch) and aural location. The author categorized 4 stimuli in terms a "+" for relevant, and a "-" for irrelevant stimulus dimensions. When the discrimination was easy for all dimensions the Nd to the target was greater than the Nd elicited by the other stimuli. But when the discrimination was hard for one of the dimensions there was increased Nd for both the target and the false alarm that shared the easier dimension with the target. The sensitivity of PN to the physical features of a stimulus (in this case which ever one was easier) suggest its role in an attentional effect involving selection by a particular feature as with the early models of attention.

Another interesting finding about the Nd was made by Hansen and Hillyard (1988) in a reexamination of the issues raised by Donald and Young (1982). Using a an auditory frequency (pitch) changing stimulus task they investigated the development of the Nd across a sequence of stimuli. What they found was that the Nd was not present for the first tone in a sequence, and did not develop fully until the third or fourth tone in a sequence. Hansen and Hillyard took this as evidence that the Nd could not be preset in advance, and thus represented an active selection system. Furthermore they characterized the development of the Nd as contingent on recent exposure to the relevant stimuli which would account for the lack of the Nd on the first trial. After the Nd developed however the active mechanism worked as an early selection process to allow more efficient processing reflected in better overt performance, (e.g. detection of the target).

Naatanen's Attentional Trace Hypothesis

In a review of the body of literature accumulated on selectional processes utilizing psychophysiological measures Naatanen (1990) offered an interesting thesis on the nature of the Nd, and the kinds of processing it reflects. Naatanen asserted that the Hansen and Hillyard (1988) finding that the Nd could not develop until the third stimulus was evidence that the selection process the Nd represented, was based on a memory representation of the target stimuli. Once the memory representation, or trace was formed then the incoming stimuli could be compared with the trace to allow for a more efficient selection of the target stimuli. Naatanen held that the Nd itself (early phase) was reflective of that kind of comparison of auditory features. Naatanen assumed that all types of feature processing correlated with the Nd would be processes invol ing attentional traces. Again, given Hansen and Hillyard's (1988) finding, this would seem to be a plausible hypothesis. Naatanen (1990) makes the empirical prediction based on the attentional trace hypothesis that, "the Nd cannot be elicited by the first relevant stimulus of the sequence, that is before the corresponding information exists in sensory memory" (pg 225).

Now we have arrived at the central question of this thesis which is concerned with a closer empirical examination of the attentional trace hypothesis. We have performed a conceptual replication of Hansen and Hillyard (1988) but also added a further stimulus feature of location to examine the Nd selection dynamics with this auditory feature as well as that of frequency. The multidimensional stimuli we have employed vary in both frequency and aural location (right vs left ear), and if the attentional trace hypothesis is correct we should expect to find that the Nd will take several trials to develop following a tone at which a subject attends an irrelevant stimulus feature. If the Nd does not occur on the first trial for the location attribute then we will have extended the attentional trace hypothesis to attributes other than frequency, and opened up the possibilities further for constraining information gathered at other levels of analysis. However even if we find that the attentional trace hypothesis can not be extended to location processing we will have learned something about the Nd itself. Specifically finding a first trial Nd for location processing, would support the position taken by the Hillyard group, which is that the Nd represents an enhancement of processing, rather than the actual initial selection itself (Hansen and Hillyard. 1980; Okita, 1981). Naatanen has criticized this view on different grounds including the (Naatanen, Ahlo, and Sams, 1985) rationale that, "it is hard to imagine a still earlier initial-selection process" (pg. 85). Thus Naatanen (1990) continues in the competing position that the Nd represents the selection process itself.

Method

Subjects

Twenty students at the University of Illinois participated in the study All subjects completed the experiment; 14 of them were male, and 6 were female. Subjects ranged in age between 19-27 years old. Sixteen of the subjects were right-handed. All subjects had normal vision or corrected to normal vision.

EEG and ERP Recording Procedure

During the experiment EEG was recorded at Fz, Cz, and Pz electrode sites referred to linked mastoids. A 10 second time constant was used during recording. To detect muscular artifact from eye movements EOG electrodes were placed above and below the right eye so that trials with eye blinks could be removed from analysis off-line. The data were digitized at 200 Hz from the period 200 msec prior to the visual cue onset at the start of a train of stimuli, until 200 msec following the removal of the cue signifying the end of a train.

In preparing the single trials for ERP averaging, all trials with EOG and muscular artifact were eliminated offline. Waveforms were filtered with a moving average low-pass filter yielding a half amplitude frequency cutoff of 8.86 Hz. The mean voltage value of the period 200 msec prior to stimulus onset was subtracted from all points in the waveform obtained.

Stimuli

The stimuli employed in the study consisted high (1500 Hz) and low (900 Hz) frequency tones. The tones were presented through headphones to the left and right ears. This created four classifications of tones which were presented at 65 Db for 100 msec with a 10 msec linear/rise fall time against a background of 55 Db white noise to mask out external noise. Stimuli were classified in this study in terms of their relationship to the exerimenters instructions. The notation represents the degree to which the stimuli was associated with the location/frequency features of the cue (e.g. the stimulus to which the subjects were instructed to respond). A complete match of frequency and location was categorized $F+L+$, a match of frequency only $F+L-$, a match of location only $F-L+$, and stimuli with neither feature $F-L-$.

The stimuli were selected on the basis of a visual cue which appeared in the center of a monitor prior to the presentation of the stimuli. (See Figure A1) The vertical arrow of the cue was used to indicate which of the two tone frequencies to select; the upward pointing arrow indicated the high tone, and the downward arrow indicated the low tone. The horizontal arrow indicated which ear to attend to, with the leftward pointing arrow indicating the left ear, and the rightward pointing arrow indicating the right ear.

Following the visual cue a train of 12-16 tones were presented for selection by the subject during which the visual cue remained on the screen. This was followed by another cue-tone train until 20 trains had passed. Eight randomized sequences of 20 trains (scenarios) were created with the constraint that a cued location and frequency would not repeat more than three times within a train. The eight scenarios of 20 trains were each repeated four times within the experiment. Each subject heard a total of 8,960 tones which were divided equally among the four tone classifications.

Procedure

The subjects participated in the experiment for two sessions. During the practice session EEG was not recorded. In this session subjects received instruction as to the task and the nature of the EEG recording of the subsequent session. At least 4 scenarios were presented to all subjects and generally subjects performance on the task during practice was similar to that obtained during the recording session by about the second scenario. Subjects were instructed to respond as quickly as possible with a button box following the detection of the currently cued stimuli. To add an incentive to perform well, subjects were also instructed that they would be paid a bonus of 1.5 cents per correct detection, and lose 1.5 cents for each miss, or false alarm accumulated during the sessions. To account for the rapid pace of tones (ISI of 350-500 msec) a hit was defined as a response within 200-600 msec after stimulus onset. Responses outside this window were classified as false alarms if they were within the window for a non-target tone, or as invalid if they didn't fit any category, (e.g. an accidental button-press). Feedback was periodically given at the end of blocks to allow the subjects to find out their currently accumulated bonus. Subjects were also instructed to attempt to suppress eye, and bodily movements during the presentation of the tones.

During the EEG recording session the eight scenarios were presented four times each with periodic breaks which yielded a total session length of around 4 hours. Breaks were given after each of the 8 scenarios of around 5 minutes, and also one longer one at the halfway point of around 20 minutes. Subjects were also instructed in this session to suppress eye and bodily movements as much as possible during the train sequence and given feedback on their task performance. During both sessions subjects sat in an experimental chamber in a recliner with a video display centered in front of them. Subjects also responded with their dominant hand on a button box placed in their lap.

Results

Three different sets of analyses are presented here which were designed to address specific questions concerning the selective processing of location and frequency features. The "Collapsed Analysis" contains response data averaged over the entire experiment and grand average ERPs. The "First Trial Analysis" examines in depth the response and ERP data of the first tone in a train following all cue switch conditions. This analysis was undertaken with Naatanen's (1990) prediction in mind on the cognitive significance of the Nd; "the Nd cannot be elicited by the first relevant stimulus of the sequence, that is before the corresponding information exists in sensory memory" (pg 225). The "Sequential Position" analysis similarly examines the data by relative positions in the train with early(pos. 1-4), middle(pos. 5-8), and late (pos. 9-12). This analysis was undertaken to examine the data for results which might support Hansen and Hillyard's (1988) work with frequency changes and the Nd which showed that the Nd could not be elicited until several trials after a change in the frequency attribute.

Collapsed Analysis

Table A1 contains the response data measures employed for means computed across all cue conditions and stimulus types. The mean reaction time was 352 msec with subjects identifying target stimuli at 95% accuracy. Subjects sensitivity to the frequency/location discrimination were assessed using a non-parametric measure A' (total) which was across cue condition and stimuli types .961.

Figures A3-A5 display the grand average ERPs for each stimulus type at each electrode. The F+L+, F+L-, and F-L+ waveforms all show a negative shift witn respect to that of the F-L- after the rise of the N1 which is indicative of the frontal Nd component. This effect is overlapped around the time of the P3 component for F+L+ (target stimuli) waveform, especially at the Pz electrode site. Table A2 contains the latencies and amplitudes of the N1 component. Table A3 displays the P3 component's amplitude and latency data which indicates a large P3 was present for F+L+ stimuli with a more posterior distribution.

Figures A6 and A7 display the mean values of the difference waves at Fz and Cz at 50msec intervals in the in the period 50-500msec subsequent to the presentation of the stimulus. Values for the F+L+ waveforms after 300msec are not displayed due to the overlap of the P3 component as stated earlier. Filled symbols in these figures represent the Nd component through negative values that differ significantly from zero. At Cz the Nd quickly developed for the F-L+ waveform at 100-150 msec post stimulus and for the others (F+L+, and F+L-) at 200-250 msec. The same pattern is evident at Fz except that the F-L+ waveform reaches significance later during the 150-200msec epoch. Table A4 presents the amplitudes of the early Nd (Nde), and late Nd (Ndl) at Fz, and Cz electrodes. During the Nde epoch (50-250msec) Nde waves were present for all F+L-, and F-L+ stimuli at both Fz, and Cz. Nde waves were not present for the F+L+ waves at Fz, but were at Cz. In the Ndl epoch Ndl waves were evident similarly for the F+L-, and F-L+ stimuli at both electrodes, but the P3 interference obscured the F+L+ waveforms

First Trial Analysis

Figures A8-A19 contains the grand average waveforms for each cue switch category averaged across all subjects. These waveforms are similar in appearance to that of the Collapsed Analysis. The difference waves are shown in figures A20-A27 at Fz and Cz in 50 msec bins as in the collapsed analysis. While these figures are similar in appearance to those obtained in he collapsed analysis, there are some important distinctions to be made. No significant frequency specific F+L- waves were to be found in any of the trials where a stimulus attribute changed. However for the location specific F-L+ waves there was significant Nd activity following all cue switch conditions. The latency of the onset of this activity began around 200-250 msec which marks the end of the Nde epoch, and the beginning of the Ndl. For the conjunction specific F+L+ waveforms significant ND activity was found at Cz only after the location switch, and no switch categories. At Fz F+L+ Nd activity was found following all cue switch conditions except for the both switch cue.

The mean amplitudes of the Nde waves are displayed in table A10, and the means for the Ndl are in table A11. As with the collapsed results the Nde amplitude is greatest at Cz, and the Ndl at Fz. No Nde was present for either the F-L+ or F+L+ stimuli. However an Ndc was present for the F+L- stimuli in the trials when no auditory feature had changed. Ndl activity was reliable on the first trial for the F-L+ stimuli following all cue switch conditions but was larger for the location and no-switch trials where the frequency was held constant [$F(1,19)=5.62$; $p=0.0285$] . Ndl activity following the F+L- stimuli on the first trial was not reliable except in the no-switch trials as with the Ndc activity.

Sequential Position Analysis

Figures A28-A60 display the grand average ERPs for each electrode and cue switch condition. These figures are similar in appearance to the corresponding figures in the collapsed and first trial analysis sets. Figures A61-A84 present the mean values of the difference waves in 50 msec bins for the epoch 50-500 msec subsequent to the presentation of the stimulus.

The amplitudes of the Ndc at Fz and Cz are contained in tables A18-A19 while the same information is displayed for the Ndl in A20-A21. The Ndc was reliably present at Cz following all cue switch conditions at all tone positions for both the F+L+, and F-L+ stimuli except for the late position in the no-switch condition with the F-L+ stimuli. For the F+L- stimuli an Ndc was present in the early positions when no-switch occurred and also at the late positions when location switched. The Ndc did reach a reliable value for F+L- stimuli at the middle positions. The Ndl was reliably present at all positions for the F+L- stimuli following the conditions of location and both switch. For the condition where the attended frequency changed a reliable Ndl was not obtained with the F+L- stimuli until the middle position continuing into the late portion. When no switch occurred the Ndl for the F+L-stimuli was present in only the early and middle positions. The Ndl was reliably present with the F-L+ stimuli at all positions following all switch conditions.

Discussion

The collapsed analysis presents waveforms that would be expected in an auditory stimulus detection experiment. Subjects performed with a high degree of accuracy and responded quickly. The grand average ERPs look normal with an N1 displayed for all stimulus types, and a P3 for the target F+L+ stimuli.

Nd Evidence of Frequency Processing

Consistent with Hansen and Hillyard (1988) findings, the Nd was not present for the processing of frequency specific stimuli on the first trial following a switch in cued frequency. The Nd development needed several trials to develop at the middle position which begins 5 trials into the train. This tends to support the hypothesis that Nd frequency processing is most effectively realized with the support of a stimulus exemplar, or attentional trace to select subsequent stimuli. This evidence also tends to paint a picture of the Nd frequency processing in this experiment as representing an active algorithm for selection, as it cannot be pre-set in advance. Since the Nd is sensitive to the stimulus feature of frequency, we also may conclude that its generator represents an early selective mechanism.

Nd Evidence of Location Processing

Unlike frequency processing, an Nd appeared for location processing specific stimuli on the first trial. It was maintained throughout the stimulus train positions and yet did not seem to require exposure to previous tones to develop. Location processing in this experiment did not seem to require an attentional trace in order for subjects to develop an Nd. Thus the location processing Nd generator appears to operate more like a passive selectional mechanism that can be preset without the need for the occurrence of a physical representation of the stimulus. As of course this is a location specific process, the algorithm looks to be an early one as with frequency processing.

Does the Nd represent the Development of an Attentional Trace?

Without a doubt, the key empirical issue that we addressed was stated by Naatanen himself in that if the attentional trace explanation is correct, than the Nd "cannot be elicited by the first relevant stimulus of the sequence, that is before the corresponding information exists in sensory memory" (pg 225). While our results support this conclusion for the frequency specific processing that Naatanen based his hypothesis on, they also show a contradiction by displaying a location specific Nd on the first trial. Thus because there is one exception it seems unlikely that the Nd represents a single global selection mechanism. Thus our results do not support Naatanen's attentional trace hypothesis of the processing which manifests itself in the Nd. These results then tend to support the Hillyard groups assertion that the Nd represents an enhancement of processing instead of a particular process. These results support a model in which location and frequency processing are distinct in terms of their algorithm given that the tones used did not differ in discriminability, or any other dimension unknown to us. We should not be too surprised to find this, given that from the work in the Neuropsychology of attention, we know there are multiple systems which seem to physically implement selective processes. It is not too hard to infer that each of these systems might use different algorithms to capture a selective effect in accordance with the physiology available. Our results here demonstrate this hypothesis that there can be distinct algorithms for the processing of different stimulus features, namely those of auditory frequency and location.

Relevance of these findings to Modern Theory

These results are consistent with several popular modern models of attention such as Treisman's feature integration theory, (Treisman and Gelade, 1980). This model posits that the physical characteristics (e.g. frequency, or location) of stimuli are processed separately and later conjoined as attention is directed towards the eliciting stimulus. ERP evidence has been cited before in the literature to support the feature integration model by illustrating the differential processing of sensory attributes (Previc and Harter, 1982; or Hillyard and Munte, 1984). The present study also follows in this line by illustrating the separate algorithms of frequency and location processing used in selecting for multidimensional auditory stimuli. So this study can support at least the initial feature analysis stage posited in Treisman's model.

These results also support the recent models of attention that Posner and colleagues have put forward from their work in

Neuropsychology, such as (Posner and Peterson, 1990). These models have emphasized the relevance of particular brain structures in operating and generating the cognitive processes necessary to capture the feature we view globally as attention. This is in essence a feature in most information processing that David Marr (1982) refers to as the *principle of modular design* which is the principle that large difficult problems, (e.g. implementing selection physiologically) are most efficiently solved by breaking them down into smaller ones. Our current data demonstrate just this by illustrating the different algorithms used to select for location, and frequency stimulus attributes. Posner also assumes that as in the feature integration model, the separate modules are all part of one system.

Our data can not address this issue as to how features are conjoined, or how selective processes are fused together. A fundamental assumption of both these recent models is that the attentional system although wired in modules, behaves globally as a whole together. Posner and Peterson (1990) describe a system, "which involves systems separate, but interconnected " (pg 35). Again this in accord with Marr's principle of modular design. Naatanen's attentional trace hypothesis is in essence, an attempt to find a global physiological correlate of selection. Instead our work has shown that the Nd does not represent a global selection process. The Nd appears not to be represent either the glue by which features are conjoined into objects, or a master selection mechanism which integrates selectional processes. However the present data are sufficient to support the notion of separate processing algorithms for different aspects of attention, in accordance with the models and observations of Treisman, Posner, Marr and their colleagues.

References

Allport, A. (1989). *Visual attention.* In M. I. Posner (Ed.), Cognitive Science (pp. 631-682) . London: Bradford/MIT Press.

Broadbent, D. E. (1958). Perception and communication New York:Pergamon.

Broadbent, D. E. (1982). *Task combination and selective intake of information.* Acta Psychologica 50:253-290.

Cowan, N. (1988). *Evolving conceptions of memory storage,selective attention, and their mutual constraints within the human information processing system.* Psychological Bulletin 163-191.

Deutsch, J.A., and Deutsch, D. (1963) *Attention:some theoretical considerations.* Psychological Review, 70, 80-90.

Donald, M.W., and Young, M.J. (1982). *A time-course analysis of attentional tuning of the auditory evoked response.* Experimental Brain Research , 46, 357-367.

Donchin, E., Ritter, W., and McCallum, W.C. (1978) *Cognitive psychophysiology: The endogenous components of the ERP.* In E.Callaway, P.Tueting, and S.H.Koslow(Eds.) Event related brain potentials in man. New York, Academic Press.

Haider, M., Spong, P., and Lindsley, D.B. (1964). *Attention, vigilance, and cortical evoked potentials in humans.* Science ,145, 180-182.

Hansen, J. C., and Hillyard, S.A. (1980) *Endogenous brain potentials associated with selective auditory attention.* Electrencephalography and Clinical Neurophysiology 75:13-21.

Hansen, J. C., and Hillyard, S.A. (1983) *Endogenous brain potentials associated with selective auditory attention.* Journal of Experimental Psychology, 9:1-19.

Hansen, J. C., and Hillyard, S.A. (1988)*Selective attention to multidimensional auditory stimuli* . Psychophysiology, 25:316-29.

Hillyard, S. A. (1981) *Selective auditory attention and early event related brain potentials: A Rejoinder.* Canadian Journal of Psychology 35:85-100.

Hillyard, S. A., Hink, R. F., Schwent, V. L., and Picton, T.W. (1973). *Electrical signs of attention in the human brain.* Science 182:177-190.

Hillyard, S. A. & Kutas, M. (1983). *Electrophysiology of cognitive processing.* Annual Review of Psychology, 34, 33-61.

Hillyard, S. A. & Munte, T.F. (1984) *Selective attention to color and location: An analysis with event related brain potentials.* Perception and Psychophysics. 36:185-196.

Kahneman, D. (1973) Attention and effort. Prentice-Hall.

Lewis, J.L. (1970). *Semantic processing of unattended messages using dichotic listening.* Journal of Experimental Psychology, 85: 225-228.

Marr, D. (1982). Vision. San Francisco: Freeman.

Naatanen, R. (1967) *Selective attention and evoked potentials* Annales Academiae Scientarum Fennicae, 151:1-226.

Naatanen, R. (1990). *The role of attention in auditory information processing as revealed by event-related brain potentials and other measures of cognitive function.* Behavioral and Brain Sciences 13:201-288.

Naatanen, R., Ahlo, K., and Sams, M. (1985) *Selective information processing and event-related potentials.* In F. Klix, R. Naatanen, and K. Zimmer (Eds.) Psychophysiological Approaches to Human Information Processing North Holland: Elsevier.

Naatanen, R., and Gaillard, A. W. K. (1978) *Early selective attention effect on evoked potential reinterpretated.* Acta Psychologica 42:313-29.

Naatanen, R., and Gaillard, A. W. K. (1983) *The orienting reflex and the N2 deflection of the event-related potential (ERP).* In A. W. K. Gaillard, & W. Ritter (Eds.) in Tutorials in ERP research: Endogenous components, Amsterdam:North-Holland.

Naatanen, R., Paavilainen, P., Ahlo, K., Reiniainen, K., & Sams, M. (1989) *Event-related potentials to infrequent decrements in duration of auditory stimuli demonstrate a trace theory in man.* Neuroscience Letters, 107:347-352.

Naatanen, R., & Picton, T. W. (1987). *The N1 wave of the human electric and magnetic response to sound: A review and an analysis of the component structure.* Psychophysiology 24:375-425.

Okita, T. (1981) *Slow negative shifts of the human event-related potential associated with selective information processing.* Biological Psychiatry, 12, 63-75.

Posner, M. I. (1978). Chronometric explorations of the mind. Hillsdale, NJ: Erlbaum.

Posner, M. I. (1982). *Cummulative development of attentional theory.* American Psychologist , 37, 168-179.

Posner, M.I., Cohen, Y., Choate, L., Hockey, R., and Maylor, E. (1984). *Sustained concentration: passive filtering or active orienting.* In: S. Kornblum and J. Requin (Eds.), Preparatory States and Processes (pp. 49-68). Hillsdale, New Jersey: Lawrence Erlbaum.

Posner, M.I., and Peterson, S.E. (1990) *The attention system of the human brain.* Annual Review of Neuroscience, 13:25-42.

Previc, H.F., and Harter, M.F. (1982) *Electrophysiological and behavioral indicants of selective attention to multifeature gratings.* Perception and Psychophysics, 32:465-472.

Schneider, W., Dumais, S.T., and Schiffrin, R.M. (1984) *Automatic and controlled processing and attention.* In R. Parrasuraman & D.R. Davies(Eds.), Varieties of Attention. New York: Academic Press.

Teece, J.J. (1972). *Contingent negative variation(CNV) and psychological processes in man.* Psychological Bulletin, 77,73-108.

Treisman, A., Squire, R., and Green J. (1974.) *Semantic processing in dichotic listening? A replication.* Memory and Cognition, 2, 641-646.

Treisman, A. (1988). *Features and objects.* Quarterly Journal of Experimental Psychology, 40a,201-237.

APPENDIX A

Table A1
Performance - Sensitivity Measures

	Mean	Standard Error
Reaction Time	352.40	5.37
Percent Correct	95.0	0.72
A'(total)	0.961	0.0058
A'(F+L-)	0.964	0.0053
A'(F-L+)	0.951	0.0075
A'(F-L-)	0.968	0.0047

Table A2
N100 Latency

	Fz		Cz		Pz	
	Mean	SE	Mean	SE	Mean	SE
F+L+	**131.25**	5.14	**129.50**	4.03	**116.75**	5.28
F+L-	**135.00**	5.15	**130.25**	3.93	**123.50**	5.78
F-L+	**135.25**	5.39	**134.00**	4.00	**129.00**	5.93
F-L-	**135.00**	5.04	**129.75**	3.33	**122.25**	5.51

N100 Amplitude

	Fz		Cz		Pz	
	Mean	SE	Mean	SE	Mean	SE
F+L+	**-3.27**	0.34	**-3.66**	0.33	**-2.36**	0.27
F+L-	**-3.44**	0.32	**-3.62**	0.33	**-2.29**	0.25
F-L+	**-3.65**	0.34	**-4.29**	0.39	**-2.74**	0.30
F-L-	**-3.56**	0.31	**-3.82**	0.35	**-2.43**	0.28

Table A3
P300 Latency

	Fz		Cz		Pz	
	Mean	SE	Mean	SE	Mean	SE
F+L+	**447.75**	11.92	**445.25**	7.17	**420.75**	7.63
F+L-	**453.25**	12.13	**460.75**	14.20	**447.50**	18.25
F-L+	**454.00**	8.03	**442.25**	13.88	**426.50**	18.08
F-L-	**448.25**	16.54	**426.75**	16.18	**464.00**	20.89

P300 Amplitude

	Fz		Cz		Pz	
	Mean	SE	Mean	SE	Mean	SE
F+L+	**1.81**	0.69	**4.99**	1.09	**6.01**	0.90
F+L-	**1.17**	0.31	**0.07**	0.31	**-0.75**	0.25
F-L+	**0.36**	0.22	**-0.26**	0.22	**-0.62**	0.25
F-L-	**1.64**	0.32	**0.67**	0.32	**-0.71**	0.33

Table A4
Nde Amplitude

	Fz			Cz		
	Mean	SE	prob.	Mean	SE	prob.
F+L+	**-1.57**	0.95	0.0575	**-3.54**	0.90	0.0004
F+L-	**-0.61**	0.27	0.0185	**-0.84**	0.26	0.0040
F-L+	**-2.14**	0.57	0.0006	**-3.66**	0.59	0.0001

Nd1 Amplitude

	Fz			Cz		
	Mean	SE	prob.	Mean	SE	prob.
F+L-	**-4.02**	0.64	0.00005	**-3.50**	0.77	0.0001
F-L+	**-9.70**	1.24	0.00005	**-6.33**	1.39	0.0001

Table A5 Performance Measures			
		Trial 1	Trial 2-12
Reaction Time	Mean	376.23	350.09
	SE	8.59	5.69
Percent Correct	Mean	91.98	95.32
	SE	1.11	0.69
A' Total	Mean	0.9292	0.9644
	SE	0.0117	0.0054
A' F+L-	Mean	0.9377	0.9670
	SE	0.0107	0.0050
A' F-L+	Mean	0.9098	0.9550
	SE	0.0142	0.0071
A' F-L-	Mean	0.9395	0.9710
	SE	0.0108	0.0044

Table A6 Performance Measures					
		Cue Switch Dimensions			
		Both	Frequency	Location	None
Reaction Time	Mean	**373.11**	**377.33**	**384.18**	**374.02**
	SE	8.71	10.37	9.57	9.48
Percent Correct	Mean	**90.30**	**92.20**	**92.20**	**93.70**
	SE	0.14	0.11	0.11	0.10
A'(total)	Mean	**0.921**	**0.930**	**0.925**	**0.945**
	SE	0.012	0.012	0.013	0.010
A'(F+L-)	Mean	**0.932**	**0.940**	**0.931**	**0.952**
	SE	0.011	0.011	0.012	0.009
A'(F-L+)	Mean	**0.895**	**0.904**	**0.908**	**0.933**
	SE	0.017	0.016	0.017	0.011
A'(F-L-)	Mean	**0.933**	**0.940**	**0.936**	**0.953**
	SE	0.011	0.011	0.012	0.009

Table A7
F-values and probabilities for tests of A'(total)

		Both	Frequency	Location	None
Both	F(1,19)	----	1.51	0.49	8.20
	prob.		0.2344	0.4919	0.0099
Frequency	F(1,19)	----	----	0.32	5.20
	prob.			0.5762	0.0344
Location	F(1,19)	----	----	----	7.58
	prob.				0.0126
F-values and probabilities for tests of A'(F+L-)					
Both	F(1,19)	----	1.86	0.04	8.02
	prob.		0.1890	0.8445	0.0107
Frequency	F(1,19)	----	----	1.61	4.88
	prob.			0.2203	0.0396
Location	F(1,19)	----	----	----	11.19
	prob.				0.0034
F-values and probabilities for tests of A'(F-L+)					
Both	F(1,19)	----	0.68	1.70	9.53
	prob.		0.4191	0.2074	0.0061
Frequency	F(1,19)	----	----	0.08	7.485
	prob.			0.7799	0.0131
Location	F(1,19)	----	----	----	4.63
	prob.				0.0445
F-values and probabilities for tests of A'(F-L-)					
Both	F(1,19)	----	1.67	0.45	8.36
	prob.		0.2123	0.5086	0.0094
Frequency	F(1,19)	----	----	0.44	6.1415
	prob.			0.5147	0.0228
Location	F(1,19)	----	----	----	8.52
	prob.				0.0088

Table A8

N100 Latency -- Cz

		Cue Switch Dimensions			
		Both	Frequency	Location	None
F+L+	Mean	**135.25**	**128.75**	**140.00**	**128.25**
	SE	4.85	6.46	5.07	4.78
F+L-	Mean	**143.50**	**145.50**	**143.00**	**139.25**
	SE	5.05	4.93	3.93	4.04
F-L+	Mean	**142.05**	**142.00**	**140.50**	**143.00**
	SE	3.96	4.79	5.20	5.03
F-L-	Mean	**143.25**	**140.50**	**141.00**	**141.50**
	SE	4.62	4.00	4.30	3.78

N100 Amplitude -- Cz

		Both	Frequency	Location	None
F+L+	Mean	**-7.68**	**-7.52**	**-8.19**	**-7.30**
	SE	0.69	0.83	0.88	0.77
F+L-	Mean	**-7.55**	**-7.30**	**-7.75**	**-8.61**
	SE	0.71	0.63	0.56	0.74
F-L+	Mean	**-8.35**	**-8.08**	**-8.42**	**-7.64**
	SE	0.74	0.67	0.90	0.68
F-L-	Mean	**-8.23**	**-8.59**	**-7.81**	**-7.62**
	SE	0.69	0.79	0.92	0.88

Table A9

P300 Amplitude -- Pz

		Cue Switch Dimensions			
		Both	Frequency	Location	None
F+L+	Mean	**5.92**	**7.15**	**7.10**	**7.44**
	SE	1.58	1.49	1.67	1.39
F+L-	Mean	**2.00**	**1.39**	**1.62**	**0.08**
	SE	0.94	0.71	0.95	0.87
F-L+	Mean	**0.84**	**1.33**	**1.51**	**1.83**
	SE	0.89	1.10	0.98	0.96
F-L-	Mean	**1.26**	**0.24**	**1.78**	**2.32**
	SE	0.98	0.98	0.94	1.11

P300 Latency targets -- Pz

		Both	Frequency	Location	None
F+L+	Mean	**433.50**	**437.50**	**433.50**	**445.00**
	SE	17.41	15.51	18.03	16.54

Table A10					
Nde Amplitude -- Fz					
		Cue Switch Dimension			
		Both	Frequency	Location	None
F+L+	**Mean**	**6.08**	**4.14**	**-1.09**	**2.29**
	SE	2.66	1.90	3.44	0.00
F+L-	**Mean**	**2.72**	**4.12**	**0.16**	*** -4.47**
	SE	2.11	1.45	2.24	2.58
F-L+	**Mean**	**0.66**	**3.84**	**-0.69**	**-0.37**
	SE	2.16	1.93	2.07	2.91
Nde Amplitude -- Cz					
		Both	Frequency	Location	None
F+L+	Mean	**0.02**	**1.23**	**-3.33**	**-0.72**
	SE	1.62	2.21	3.28	2.27
F+L-	Mean	**1.33**	**2.98**	**-0.01**	**** -5.08**
	SE	2.01	1.54	2.15	1.80
F-L+	Mean	**-2.43**	**0.73**	**+ -2.78**	**-2.86**
	SE	2.21	2.10	1.66	2.88

** $p<.01$
* $p<.05$, one tailed test of $t<0$
+ $p<.10$

Table All

Nd1 Amplitude -- Fz

		Cue Switch Dimensions			
		Both	Frequency	Location	None
F+L-	Mean	**2.24**	**1.62**	**-3.50**	**** -11.20**
	SE	1.84	2.25	2.77	3.52
F-L+	Mean	**** -10.85**	*** -7.80**	**** -14.55**	**** -14.57**
	SE	2.55	3.63	3.79	3.20

Nd1 Amplitude -- Cz

		Both	Frequency	Location	None
F+L-	Mean	**3.03**	**1.28**	**-1.04**	**** -10.94**
	SE	2.43	2.73	2.54	3.31
F-L+	Mean	*** -6.78**	**-1.91**	*** -6.94**	*** -9.01**
	SE	2.92	4.04	3.47	4.27

** p<.01
* p<.05, one tailed test of t<0
+ p<.10

Table A12

Performance Measures

		Cue Switch Dimensions			
		Both	Frequency	Location	None
Reaction Time					
Early	Mean	**351.99**	**353.08**	**354.53**	**349.99**
	SE	6.48	6.81	6.94	6.67
Middle	Mean	**350.36**	**347.82**	**345.83**	**350.02**
	SE	5.33	5.72	6.22	5.74
Late	Mean	**357.02**	**351.99**	**356.15**	**352.45**
	SE	5.68	5.76	5.35	5.21
Percent Correct					
Early	Mean	**93.60**	**93.90**	**94.20**	**95.00**
	SE	0.90	0.90	0.90	0.70
Middle	Mean	**95.60**	**95.60**	**95.60**	**95.90**
	SE	0.60	0.60	0.60	0.50
Late	Mean	**95.20**	**95.60**	**95.00**	**95.10**
	SE	0.70	0.60	0.70	0.70

Table A13
Sensitivity Measures

		Cue Switch Dimensions			
		Both	Frequency	Location	None
A'(total)					
Early	Mean	**0.9460**	**0.9490**	**0.9540**	**.9610**
	SE	0.0080	0.0080	0.0080	0.0060
Middle	Mean	**0.9660**	**0.9660**	**0.9670**	**0.9690**
	SE	0.0050	0.0040	0.0050	0.0040
Late	Mean	**0.9620**	**0.9670**	**0.9630**	**0.9640**
	SE	0.0060	0.0050	0.0050	0.0050
A'(F+L-)					
Early	Mean	**0.9510**	**0.9540**	**0.9570**	**0.9640**
	SE	0.0080	0.0080	0.0070	0.0060
Middle	Mean	**0.9690**	**0.9690**	**0.9700**	**0.9720**
	SE	0.0040	0.0040	0.0040	0.0030
Late	Mean	**0.9660**	**0.9680**	**0.9640**	**0.9680**
	SE	0.0050	0.0050	0.0050	0.0040
A'(F-L+)					
Early	Mean	**0.9340**	**0.9340**	**0.9420**	**0.9530**
	SE	0.0100	0.0110	0.0100	0.0080
Middle	Mean	**0.9580**	**0.9560**	**0.9570**	**0.9610**
	SE	0.0070	0.0060	0.0060	0.0050
Late	Mean	**0.9500**	**0.9570**	**0.9550**	**0.9550**
	SE	0.0080	0.0070	0.0070	0.0070
A'(F-L-)					
Early	Mean	**0.9540**	**0.9580**	**0.9610**	**0.9680**
	SE	0.0070	0.0070	0.0070	0.0050
Middle	Mean	**0.9730**	**0.9730**	**0.9740**	**0.9740**
	SE	0.0040	0.0030	0.0040	0.0030
Late	Mean	**0.9690**	**0.9730**	**0.9700**	**0.9740**
	SE	0.0040	0.0040	0.0040	0.0040

Table A14						
N100 Latency -- Cz						
			Cue Switch Dimesnions			
			Both	Frequency	Location	None
F+L+	Early	Mean	**133.25**	**128.75**	**130.75**	**134.75**
		SE	4.50	3.88	3.86	5.34
	Middle	Mean	**128.00**	**127.50**	**127.25**	**119.75**
		SE	4.19	5.34	5.30	4.69
	Late	Mean	**133.50**	**129.75**	**130.00**	**133.50**
		SE	4.81	5.16	5.43	4.79
F+L-	Early	Mean	**135.75**	**133.25**	**132.50**	**133.50**
		SE	4.59	5.23	3.58	3.99
	Middle	Mean	**128.50**	**128.75**	**124.50**	**127.00**
		SE	4.06	4.24	4.43	4.91
	Late	Mean	**129.75**	**131.00**	**132.00**	**128.25**
		SE	5.46	4.90	4.40	5.07
F-L+	Early	Mean	**137.00**	**134.50**	**134.50**	**136.50**
		SE	3.54	3.46	3.90	3.16
	Middle	Mean	**130.75**	**131.75**	**131.75**	**136.50**
		SE	4.58	3.83	5.02	4.56
	Late	Mean	**139.75**	**130.75**	**138.00**	**136.00**
		SE	4.62	5.65	4.90	5.37
F-L-	Early	Mean	**132.50**	**135.50**	**131.75**	**129.50**
		SE	3.90	3.53	3.23	3.05
	Middle	Mean	**129.00**	**125.00**	**135.75**	**131.00**
		SE	4.13	4.17	5.07	3.51
	Late	Mean	**128.00**	**130.25**	**133.33**	**133.75**
		SE	4.82	4.42	4.64	4.96

Table A15

N100 Amplitude -- Cz

			Cue Switch Dimensions			
			Both	Frequency	Location	None
F+L+	Early	Mean	**-5.22**	**-5.21**	**-5.08**	**-5.61**
		SE	0.42	0.51	0.44	0.49
	Middle	Mean	**-4.06**	**-3.61**	**-3.51**	**-3.49**
		SE	0.38	0.44	0.48	0.38
	Late	Mean	**-3.35**	**-3.04**	**-3.09**	**-2.94**
		SE	0.41	0.38	0.38	0.48
F+L-	Early	Mean	**-5.25**	**-5.22**	**-4.93**	**-5.64**
		SE	0.44	0.48	0.47	0.49
	Middle	Mean	**-3.49**	**-3.58**	**-3.45**	**-3.14**
		SE	0.32	0.40	0.33	0.34
	Late	Mean	**-2.95**	**-2.98**	**-2.96**	**-3.32**
		SE	0.41	0.42	0.33	0.49
F-L+	Early	Mean	**-5.98**	**-6.50**	**-6.41**	**-5.85**
		SE	0.50	0.48	0.59	0.44
	Middle	Mean	**-4.11**	**-4.37**	**-4.36**	**-4.02**
		SE	0.37	0.40	0.51	0.52
	Late	Mean	**-3.86**	**-3.45**	**-3.17**	**-3.16**
		SE	0.43	0.44	0.41	0.36
F-L-	Early	Mean	**-5.57**	**-5.49**	**-5.31**	**-5.58**
		SE	0.43	0.54	0.53	0.40
	Middle	Mean	**-3.91**	**-3.93**	**-3.30**	**-3.65**
		SE	0.40	0.39	0.37	0.47
	Late	Mean	**-3.19**	**-3.18**	**-2.95**	**-3.17**
		SE	0.36	0.35	0.37	0.46

Table A16

F-values and probabilities for target vs non-target comparisons at Pz

		Both	Frequency	Location	None
Early	F(1,19)	36.93	52.36	34.09	33.37
	prob.	0.0001	0.0001	0.0001	0.0001
Middle	F(1,19)	40.29	40.38	34.50	33.86
	prob.	0.0001	0.0001	0.0001	0.0001
Late	F(1,19)	35.59	33.78	41.78	36.03
	prob.	0.0001	0.0001	0.0001	0.0001

Table A17

P300 Latency--Targets at Pz						
			Cue Switch Dimensions			
			Both	Frequency	Location	None
F+L+	Early	Mean	**413.75**	**420.00**	**410.75**	**401.75**
		SE	9.13	10.96	7.27	7.25
	Middle	Mean	**420.50**	**407.75**	**415.00**	**409.00**
		SE	7.55	7.07	7.50	8.19
	Late	Mean	**425.75**	**431.50**	**425.75**	**423.50**
		SE	9.59	6.54	8.82	9.55
P300 Amplitude--Targets at Pz						
			Both	Frequency	Location	None
F+L+	Early	Mean	**6.07**	**6.25**	**6.42**	**5.87**
		SE	1.11	0.94	1.04	1.03
	Middle	Mean	**6.40**	**6.35**	**6.21**	**6.89**
		SE	0.58	0.90	0.92	1.00
	Late	Mean	**5.99**	**5.91**	**6.38**	**5.18**
		SE	1.42	1.00	0.92	0.76

Table A18

Nde Amplitude--Fz

			Cue Switch Dimensions			
			Both	Frequency	Location	None
F+L+	Early	Mean	-0.65	0.23	-1.15	-1.98
		SE	1.49	1.47	1.48	1.46
	Middle	Mean	+ -2.34	+ -2.06	-2.05	-1.88
		SE	1.58	1.47	1.65	1.58
	Late	Mean	-0.49	+ -2.01	+ -2.02	* -3.12
		SE	1.03	1.37	1.21	1.35
F+L-	Early	Mean	0.66	0.30	0.52	* -1.87
		SE	1.04	1.10	1.09	1.04
	Middle	Mean	-0.82	-0.97	* -1.04	-0.00
		SE	0.95	1.37	0.55	1.25
	Late	Mean	0.22	-0.02	+ -1.10	+ -1.59
		SE	0.77	0.66	0.82	0.96
F-L+	Early	Mean	** -3.32	* -2.81	** -2.51	+ -1.84
		SE	1.18	1.30	0.96	1.12
	Middle	Mean	* -2.04	* -2.13	** -3.25	** -3.10
		SE	0.84	1.13	1.27	1.15
	Late	Mean	-1.53	* -1.99	-0.82	-1.27
		SE	1.32	0.93	0.84	1.34

** p<.01
* p<.05, one tailed test of t<0

Table A19						
Nde Amplitude--Cz						
			Cue Switch Dimensions			
			Both	Frequency	Location	None
F+L+	Early	Mean	* **2.76**	** **-2.96**	** **-3.73**	** **-5.00**
		SE	1.42	1.38	1.30	1.38
	Middle	Mean	** **-4.39**	** **-4.28**	* **-4.01**	* **-2.71**
		SE	1.44	1.37	1.90	1.40
	Late	Mean	* **-3.44**	** **-3.73**	** **-3.93**	** **-4.38**
		SE	1.41	0.00	1.25	1.30
F+L-	Early	Mean	**-0.68**	**-1.16**	**0.02**	* **-2.58**
		SE	1.03	1.04	1.08	0.96
	Middle	Mean	**-0.77**	**-0.49**	+ **-1.16**	**0.80**
		SE	1.01	1.15	0.71	1.17
	Late	Mean	**0.24**	**-1.05**	* **-1.38**	+ **-1.55**
		SE	0.64	0.80	0.79	1.07
F-L+	Early	Mean	** **-3.86**	** **-4.92**	** **-5.98**	** **-3.80**
		SE	1.26	1.19	0.87	0.98
	Middle	Mean	** **-4.10**	** **-3.45**	** **-5.33**	** **-3.45**
		SE	0.95	1.14	1.39	1.32
	Late	Mean	** **-3.42**	** **-2.98**	** **-2.82**	+ **-2.08**
		SE	1.18	0.78	0.95	1.24

** p<.01
* p<.05, one tailed test of t<0

Table A20

Nd1 Amplitude--Fz

			Cue Switch Dimensions			
			Both	Frequency	Location	None
F+L-	Early	Mean	* -2.76	-1.53	* -3.32	** -6.29
		SE	1.53	1.53	1.31	1.74
	Middle	Mean	** -4.42	** -4.40	** -3.22	+ -2.28
		SE	1.51	1.71	0.81	1.61
	Late	Mean	** -3.88	* -3.65	** -5.33	** -5.31
		SE	1.44	1.49	1.31	1.45
F-L+	Early	Mean	**-10.22	**-11.60	** -11.60	** -9.14
		SE	1.69	1.91	1.80	2.06
	Middle	Mean	** -8.75	** -9.90	** -10.86	** -8.65
		SE	1.79	1.78	2.10	2.20
	Late	Mean	** -8.57	** -8.38	** -7.52	** -6.73
		SE	2.04	1.68	1.82	1.74

** p<.01
* p<.05, one tailed test of t<0
\+ p<.10

Table A21						
Nd1 Amplitude--Cz						
			Cue Switch Dimensions			
			Both	Frequency	Location	None
F+L-	Early	Mean	* -2.60	+ -2.01	-1.70	** -5.85
		SE	1.45	1.29	1.71	1.91
	Middle	Mean	-2.19	** -4.79	* -2.15	-0.85
		SE	2.05	1.12	1.07	1.63
	Late	Mean	** -3.47	** -5.01	** -5.28	* -4.58
		SE	1.21	1.62	1.65	1.85
F-L+	Early	Mean	* -4.88	** -7.39	** -9.58	+ -3.67
		SE	2.02	2.00	1.98	2.52
	Middle	Mean	** -6.33	** -6.99	** -7.60	* -4.37
		SE	2.23	1.97	1.88	2.47
	Late	Mean	** -6.07	** -5.85	** -6.63	* -4.25
		SE	1.73	1.45	2.07	1.73

** p<.01
* p<.05, one tailed test of t<0
+ p<.10

Table A22

Nde (F-L+) - (F+L-) Amplitude - Fz

		Cue Switch Dimension			
		Both	Frequency	Location	None
Early	Mean	** -3.97	** -3.45	* -3.03	0.03
	SE	1.25	1.35	1.50	1.26
Middle	Mean	+ -1.22	-1.14	+ -2.21	* -3.05
	SE	0.71	1.19	1.29	1.28
Late	Mean	* -1.75	* -1.97	0.28	0.32
	SE	0.97	0.97	0.86	1.23

Ndl (F-L+) - (F+L-) Amplitude - Fz

		Both	Frequency	Location	None
Early	Mean	** -7.46	** -10.11	** -8.28	+ -2.84
	SE	1.96	21.52	2.18	1.82
Middle	Mean	* -4.33	** -5.50	** -7.64	** -6.37
	SE	2.00	1.91	2.07	2.27
Late	Mean	** -4.69	* -4.73	+ -2.19	-1.42
	SE	1.52	2.16	1.42	1.70

** p<.01
* p<.05, one tailed test of t<0
+ p<.10

Table A23

Nde (F-L+) - (F+L-) Amplitude - Cz

		Cue Switch Dimension			
		Both	Frequency	Location	None
Early	Mean	** -3.18	** -3.69	** -6.00	-1.21
	SE	1.18	1.25	1.51	1.24
Middle	Mean	** -3.33	** -2.96	** -4.17	** -4.26
	SE	0.91	1.13	1.43	1.24
Late	Mean	** -3.67	* -1.92	-1.44	-0.53
	SE	1.06	0.86	1.11	0.95

Nd1 (F-L+) - (F+L-) Amplitude - Cz

		Both	Frequency	Location	None
Early	Mean	-2.28	** -5.91	** -7.88	2.17
	SE	2.23	2.06	2.21	2.23
Middle	Mean	* -4.14	+ -2.20	** -5.45	+ -3.52
	SE	2.13	1.66	1.81	2.11
Late	Mean	+ -2.60	-0.84	-1.35	0.33
	SE	1.70	1.82	1.43	1.55

** p<.01
* p<.05, one tailed test of t<0
+ p<.10

Figure A1: Visual Cues

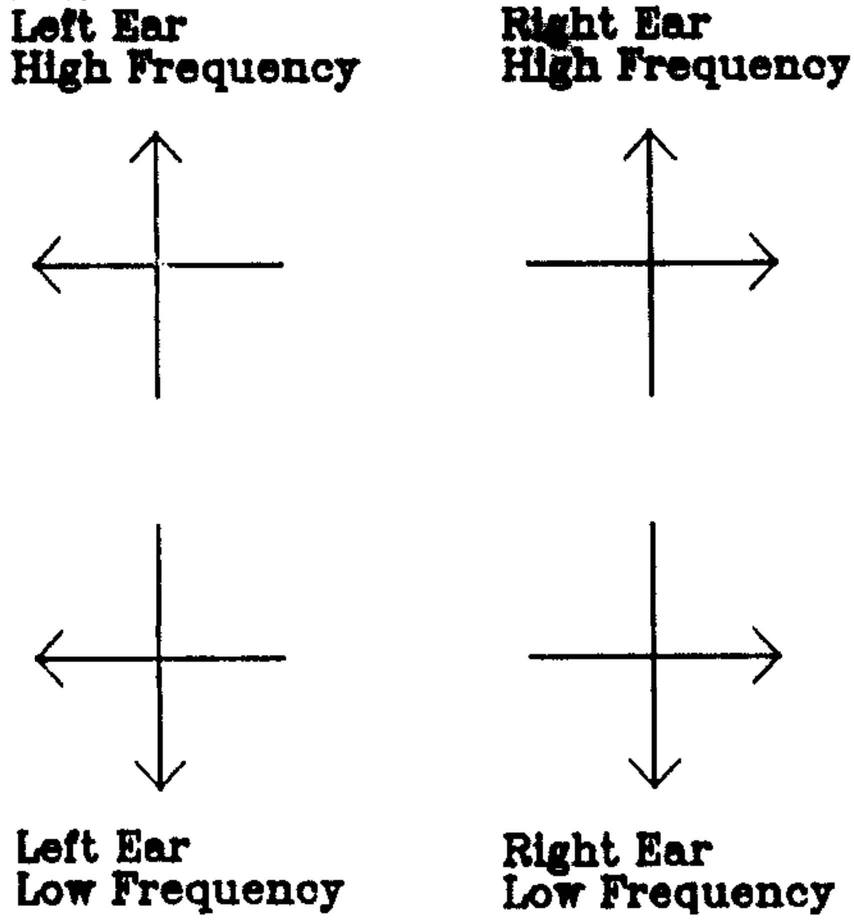

Figure A2: Task Schematic

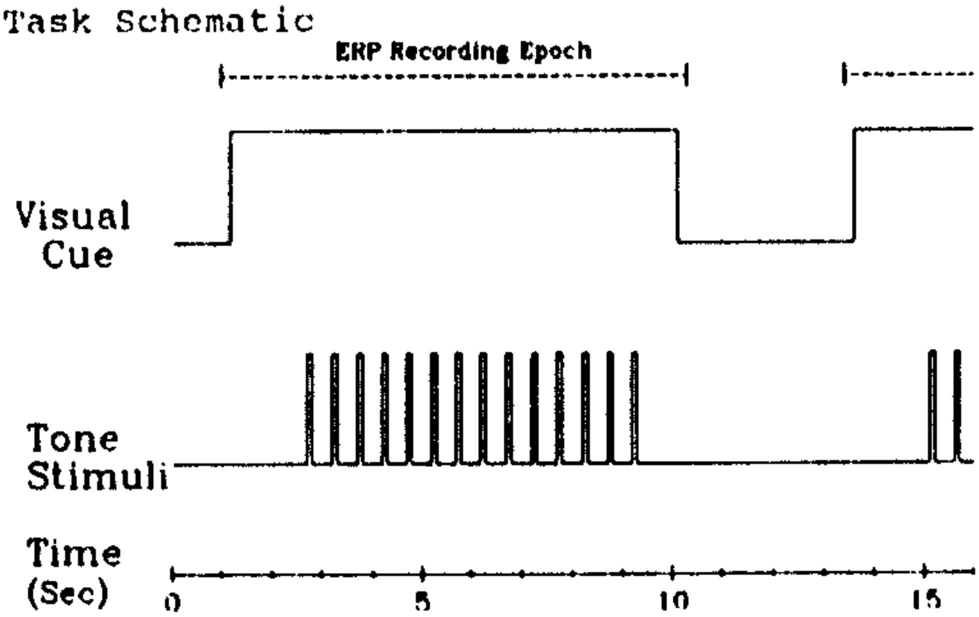

Figure A3: Collapsed Analysis - Grand Average ERPs at Fz

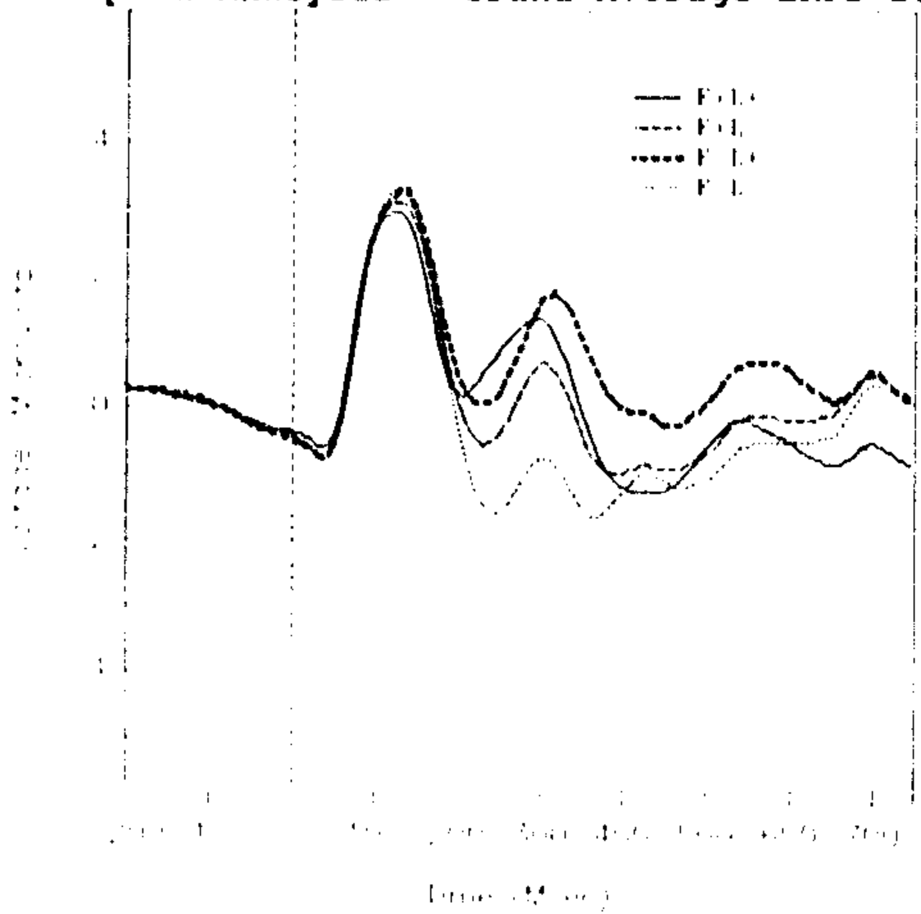

Figure A4: Collapsed Analysis - Grand Average ERPs at Cz

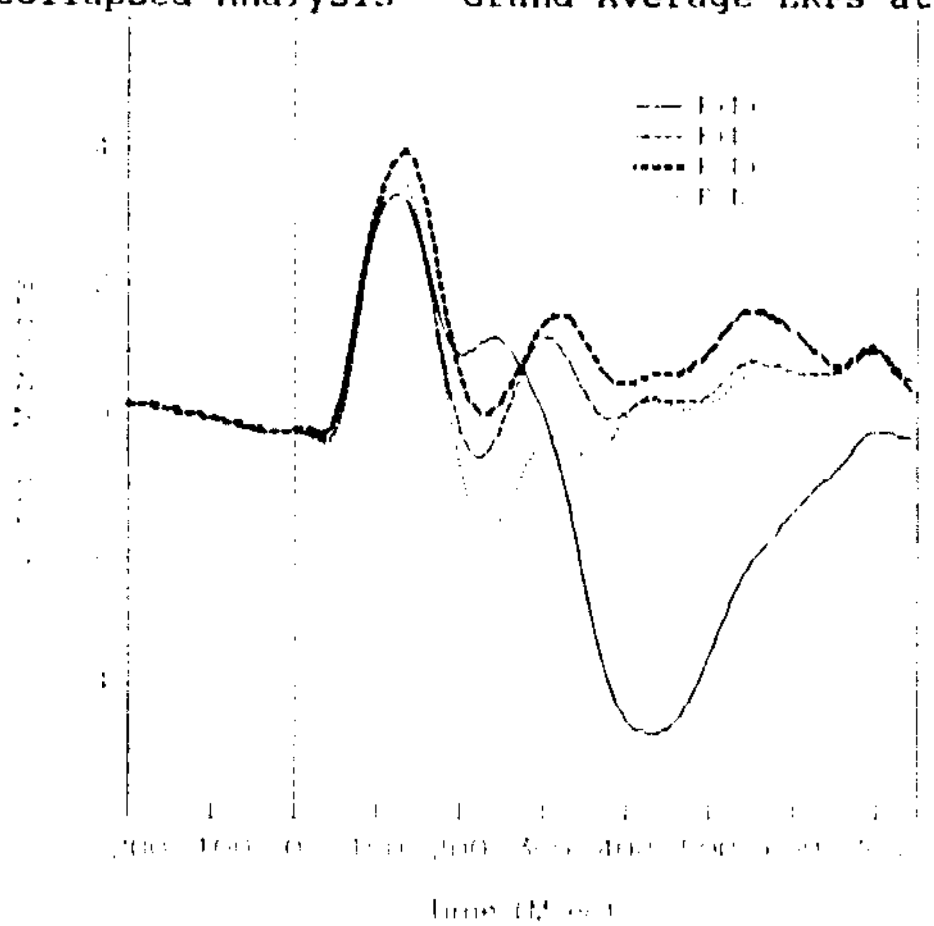

Figure A5: Collapsed Analysis - Grand Average ERPs at Fz

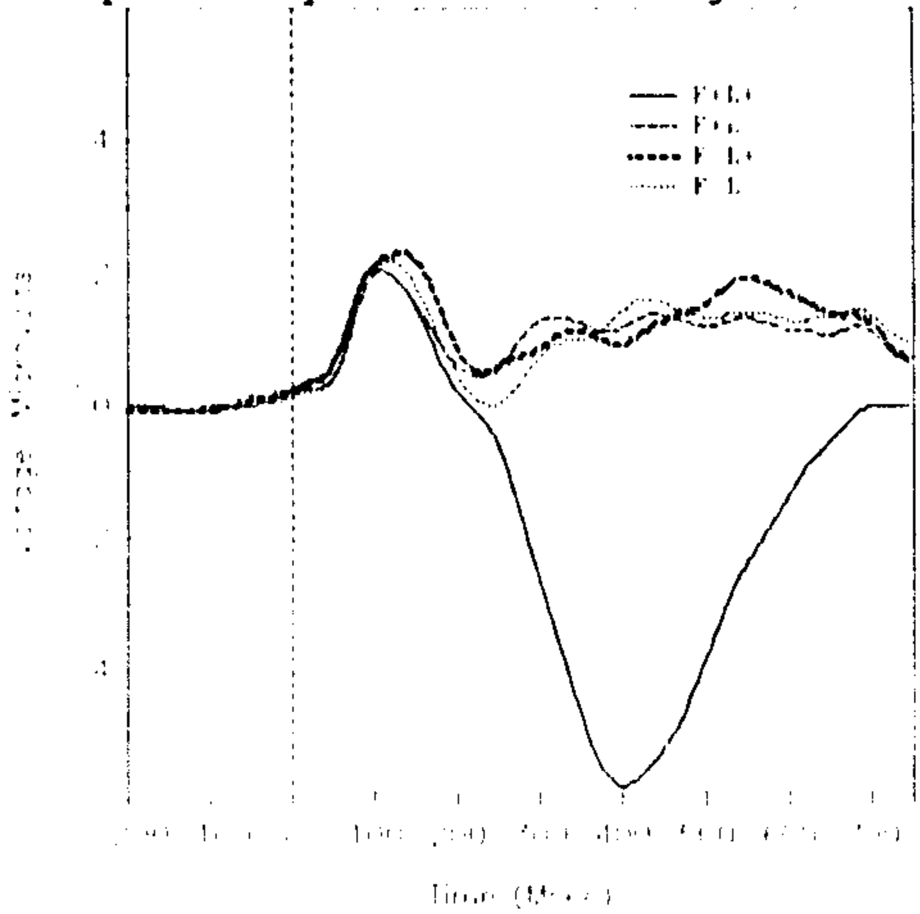

Figure A6: Collapsed Analysis - Nd Area at Fz

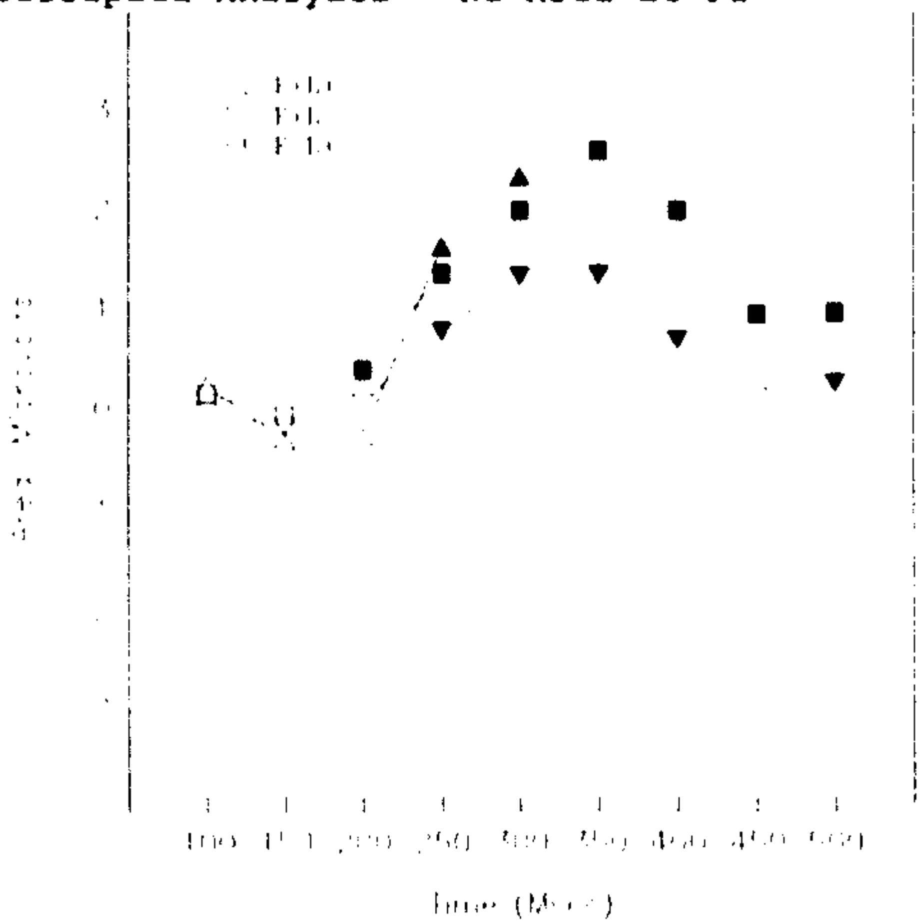

Figure A7: Collapsed Analysis - Nd Area at Cz

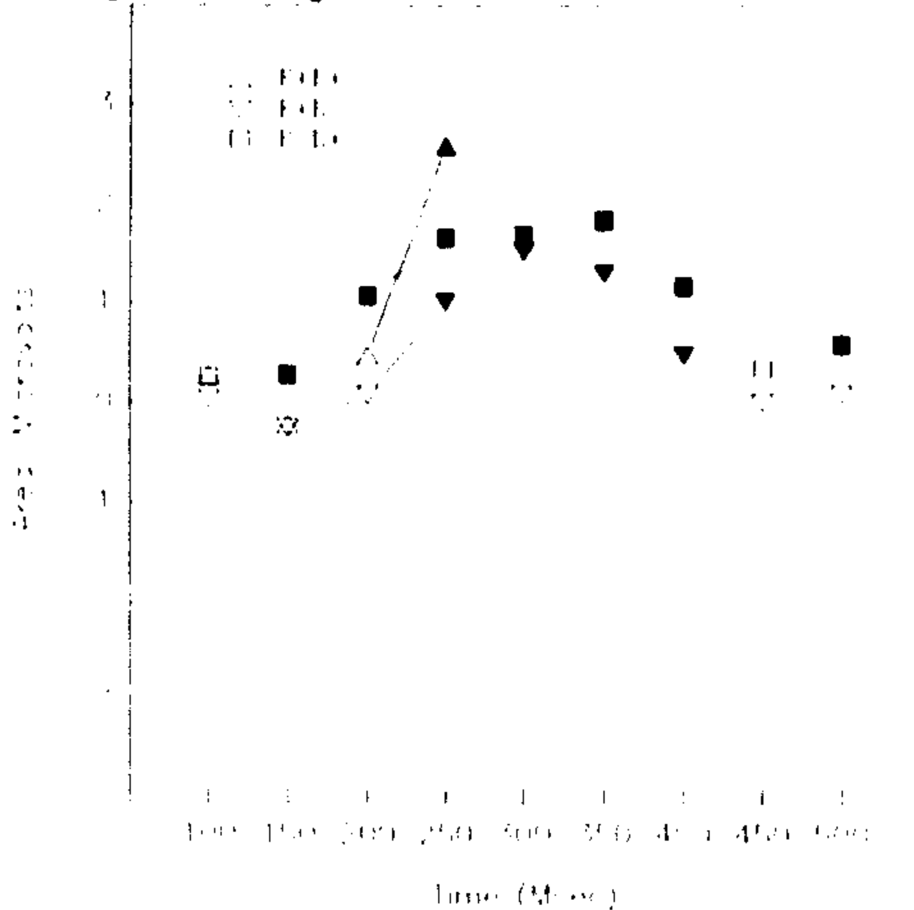

Figure A8: First Trial Analysis - Average ERPs at Fz for Both Switch

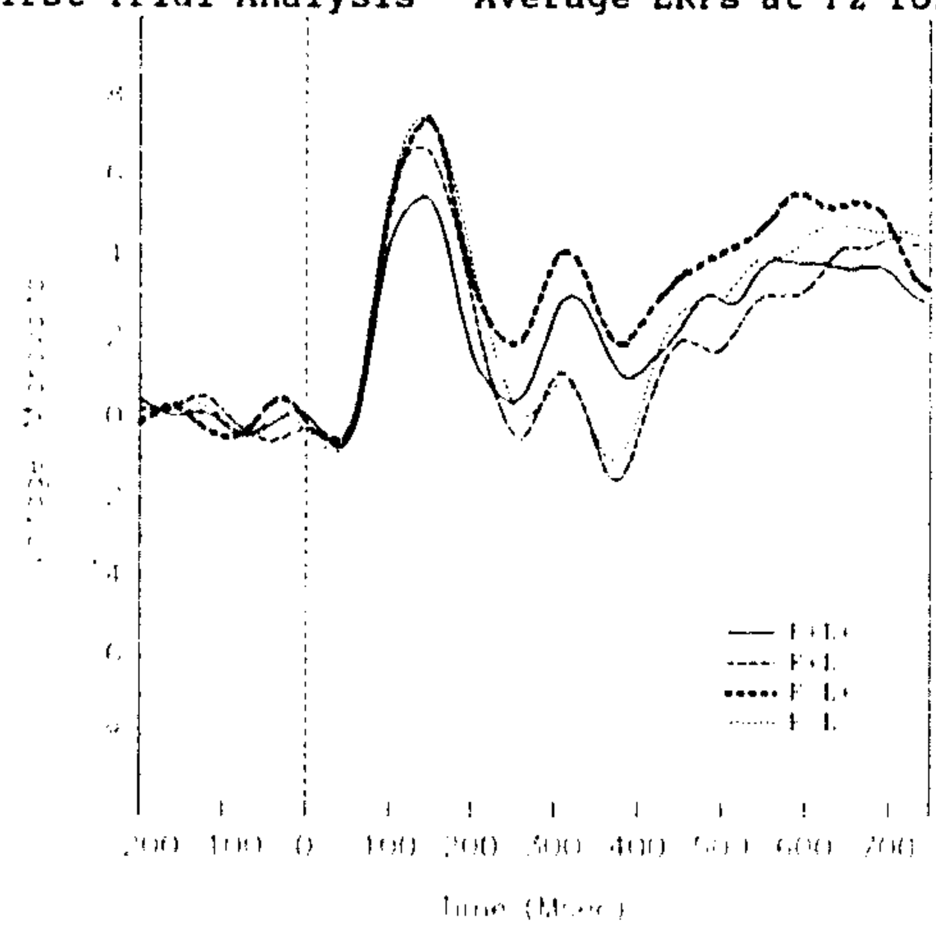

Figure A9: First Trial Analysis - Average ERPs at Fz for Frequency Switch

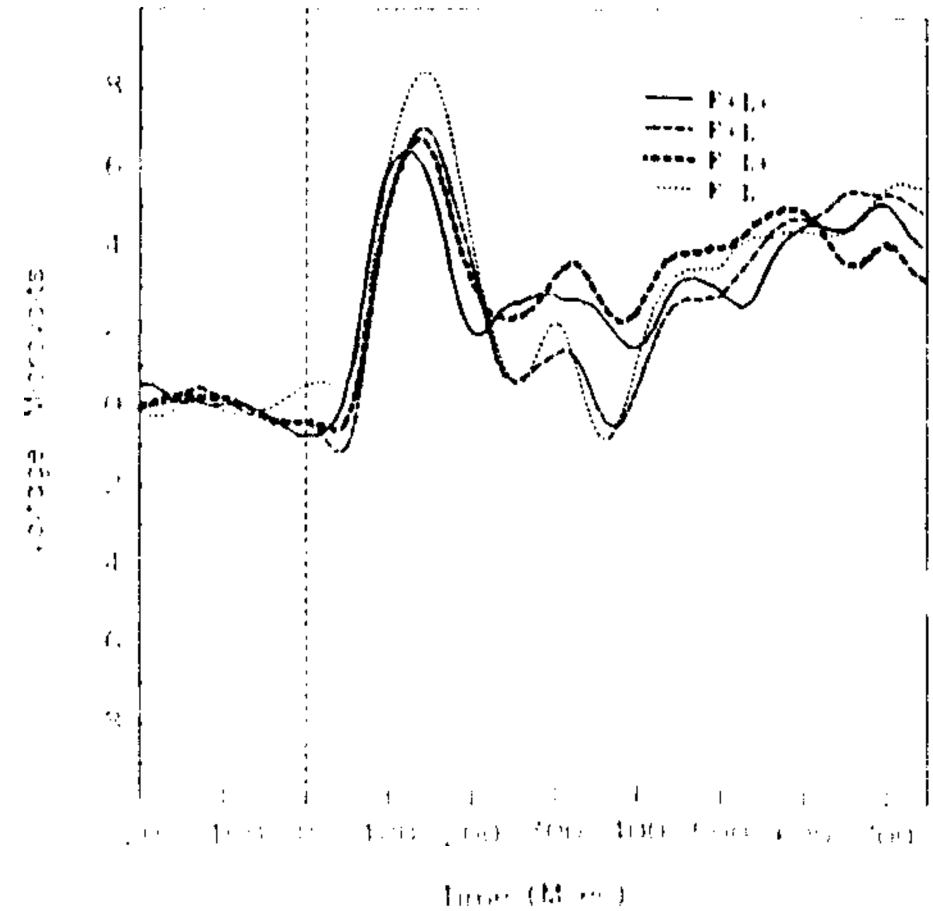

Figure A10: First Trial Analysis - Average ERPs at Fz for Location Switch

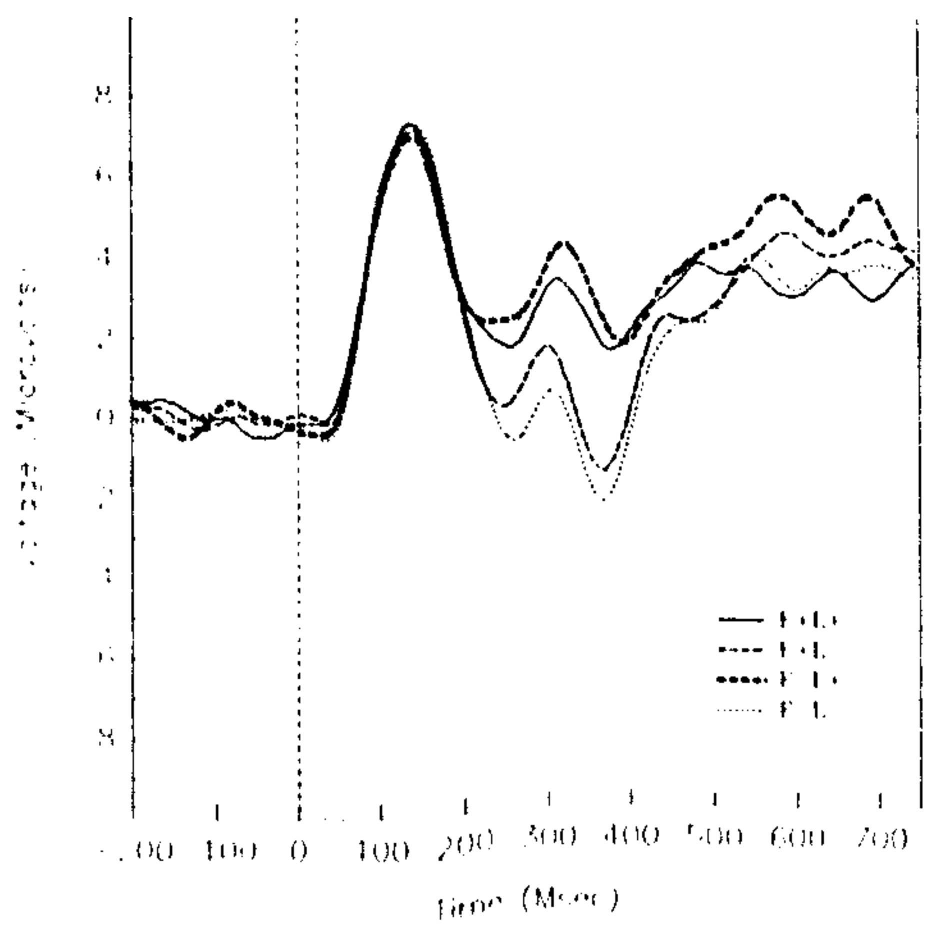

Figure A11: First Trial Analysis - Average ERPs at Fz for No Switch

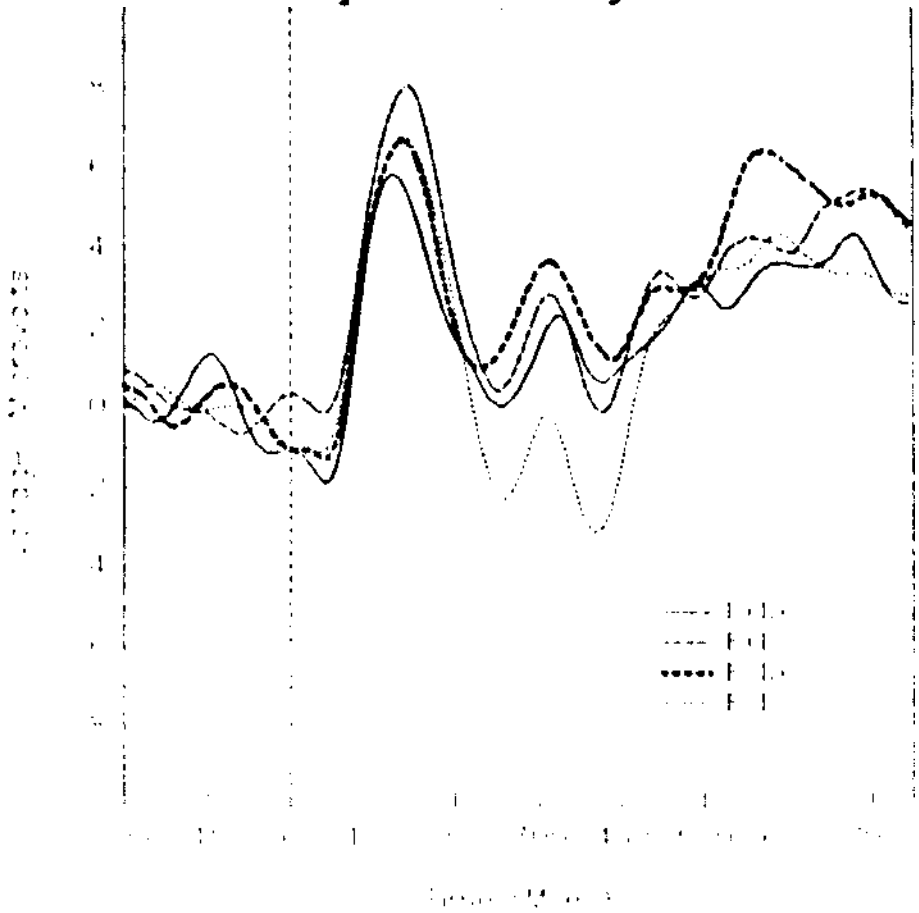

Figure A12: First Trial Analysis - Average ERPs at Cz for Both Switch

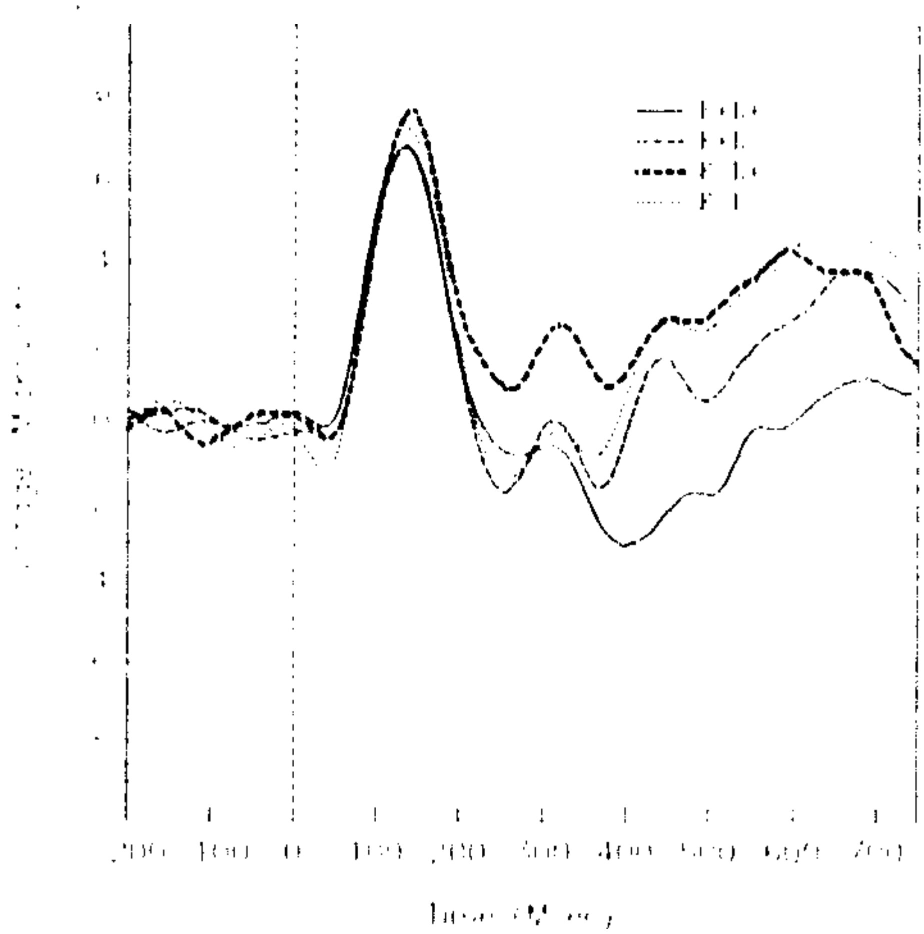

Figure A13: First Trial Analysis - Average ERPs at Cz for Frequency Switch

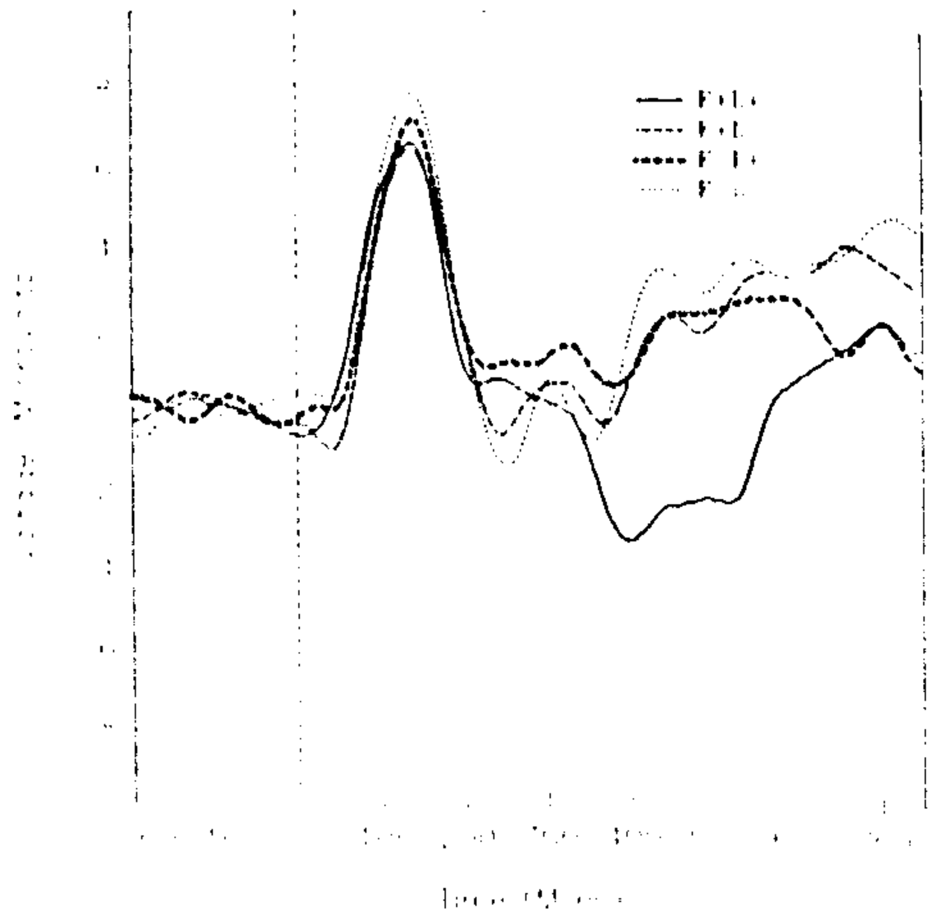

Figure A14: First Trial Analysis - Average ERPs at Cz for Location Switch

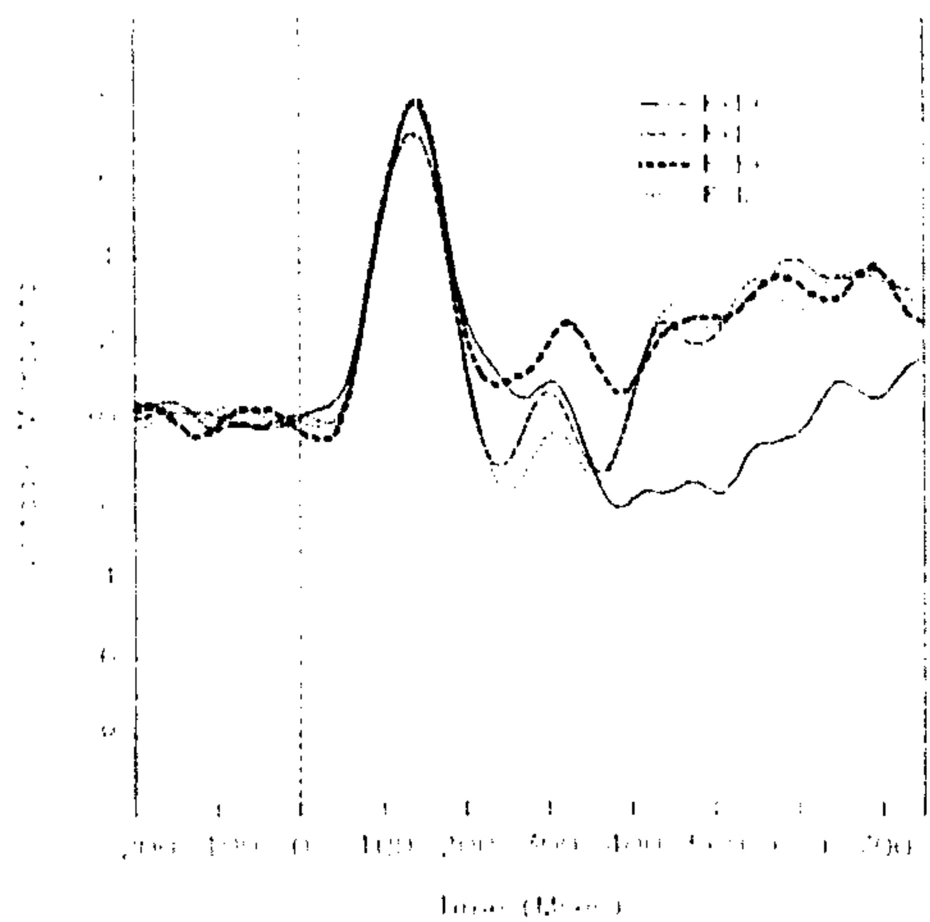

Figure A15: First Trial Analysis - Average ERPs at Cz for No Switch

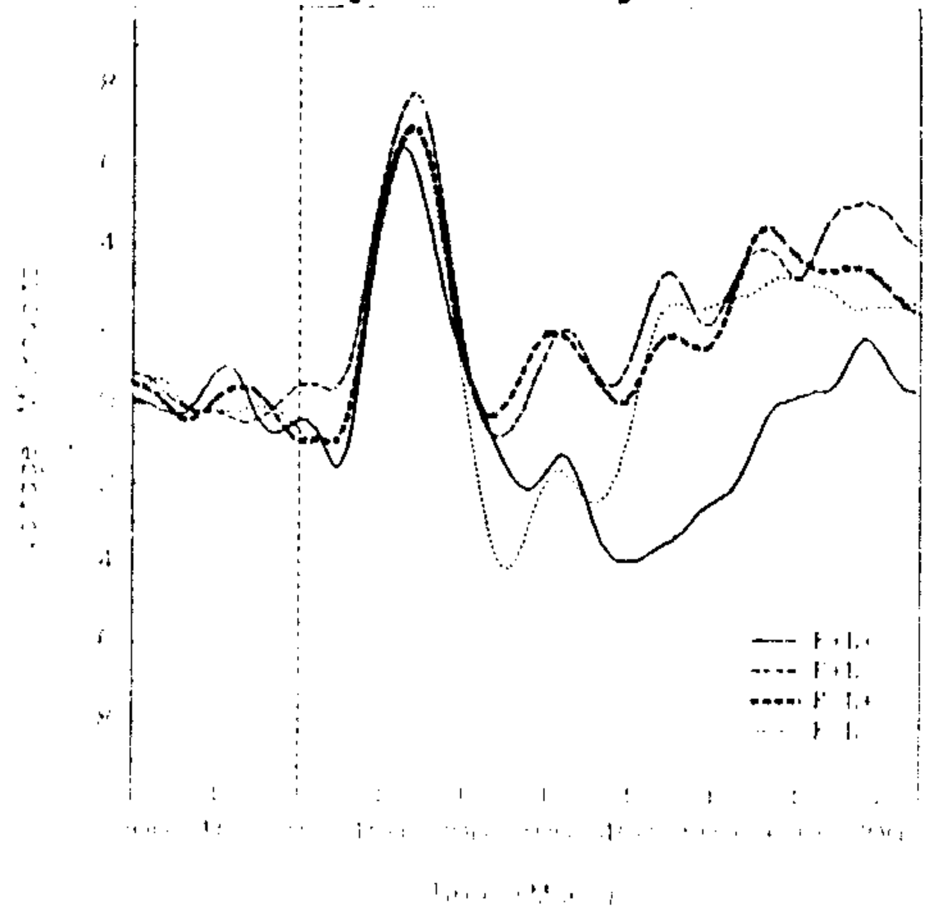

Figure A16: First Trial Analysis - Average ERPs at Pz for Both Switch

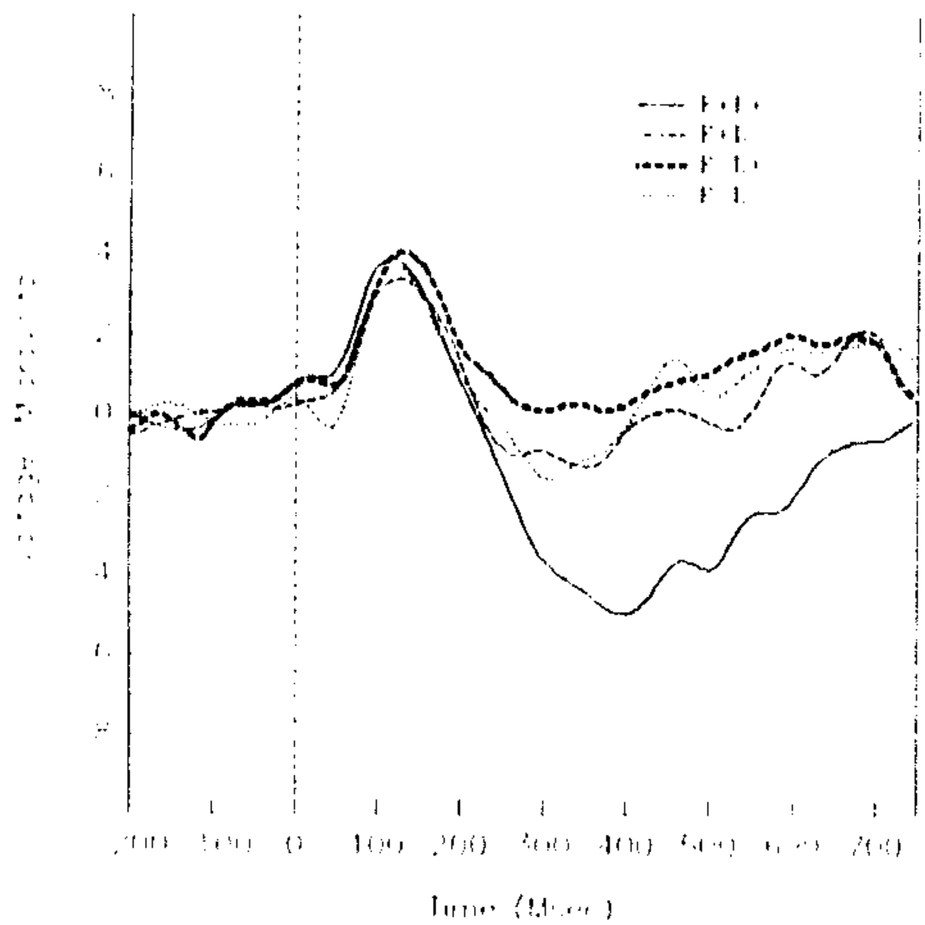

Figure A17: First Trial Analysis - Average ERPs at Pz for Frequency Switch

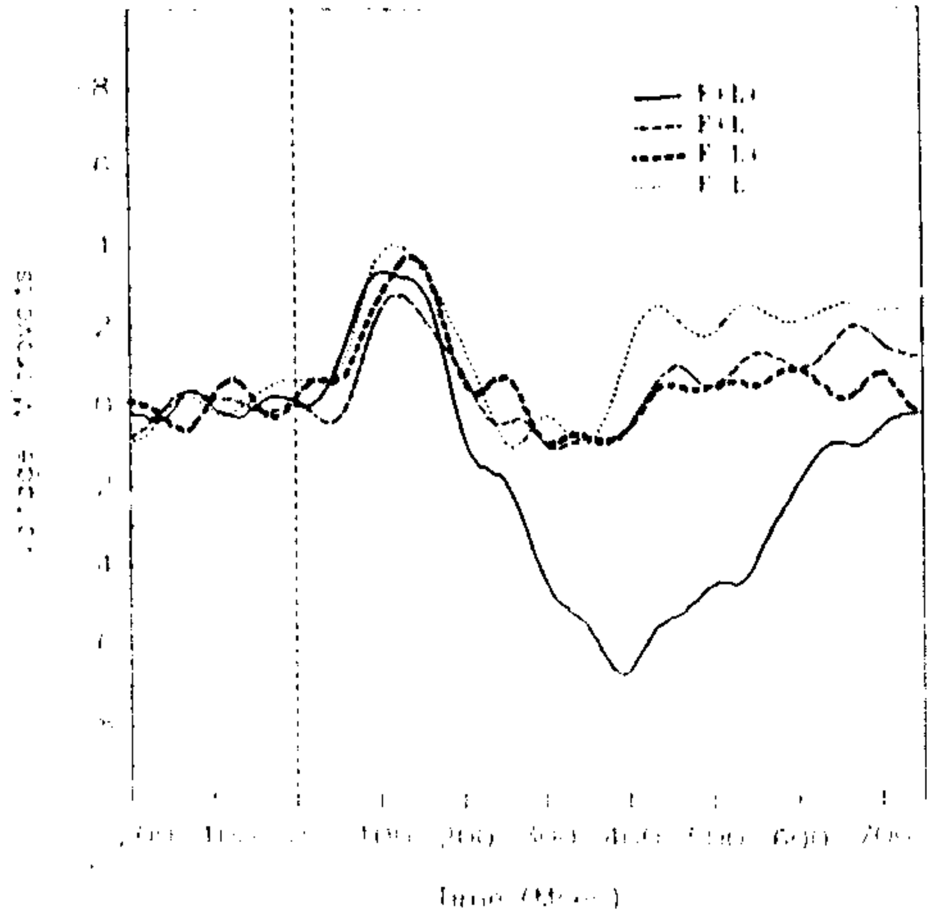

Figure A18: First Trial Analysis - Average ERPs at Pz for Location Switch

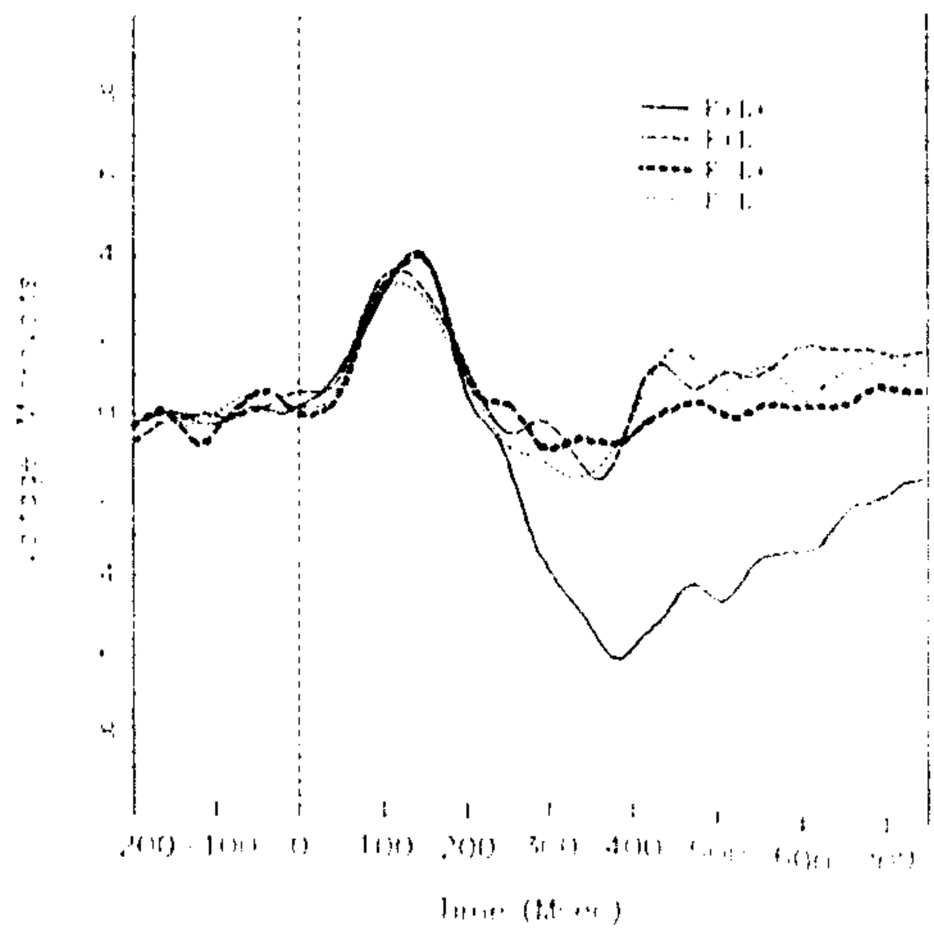

Figure A19: First Trial Analysis - Average ERPs at Pz for No Switch

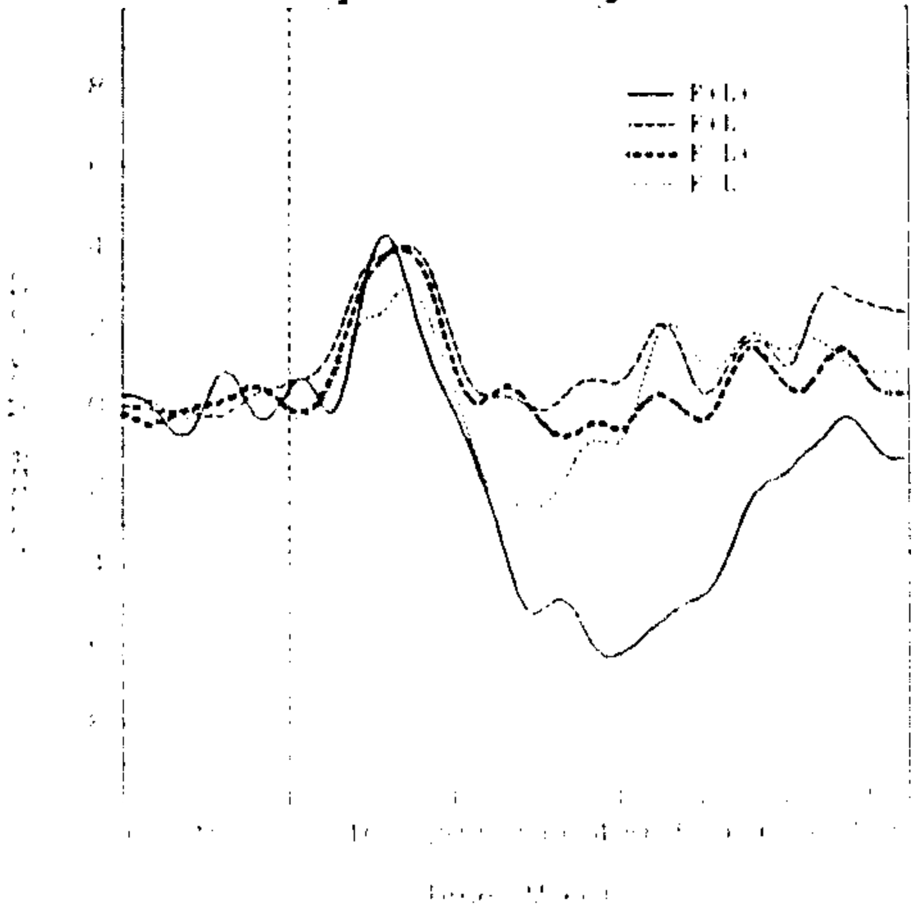

Figure A20: First Trial Analysis - Nd Area at Fz for Both Switch

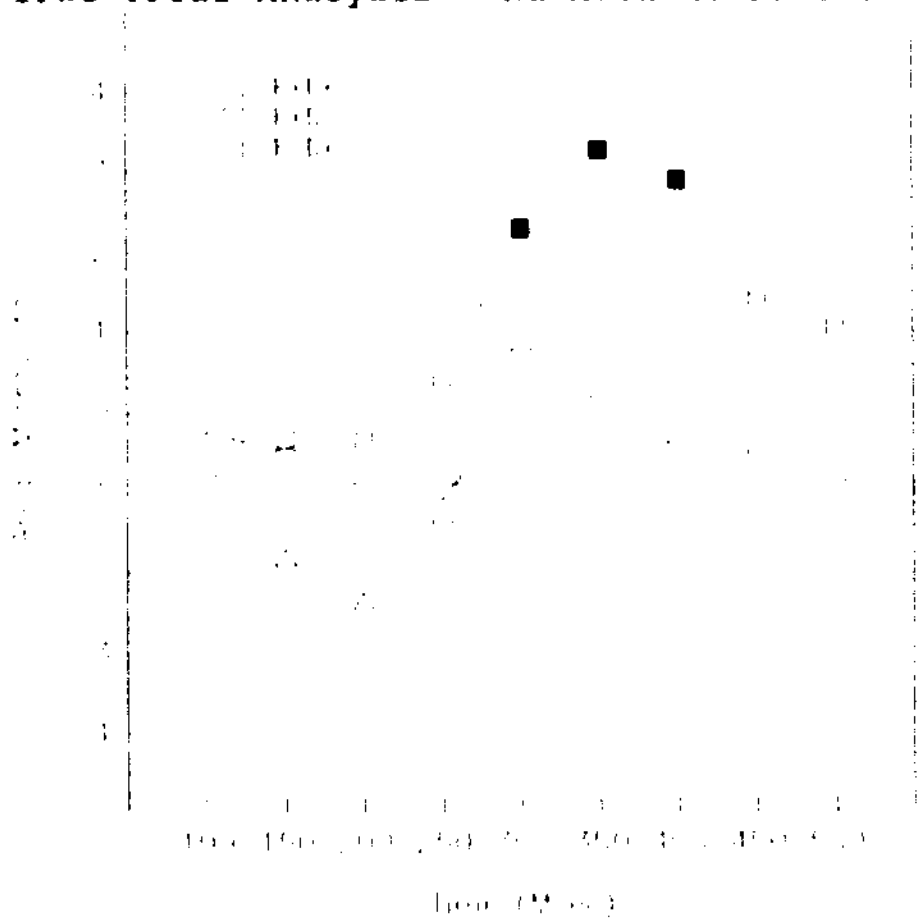

Figure A21: First Trial Analysis - Nd Area at Fz for Frequency Switch

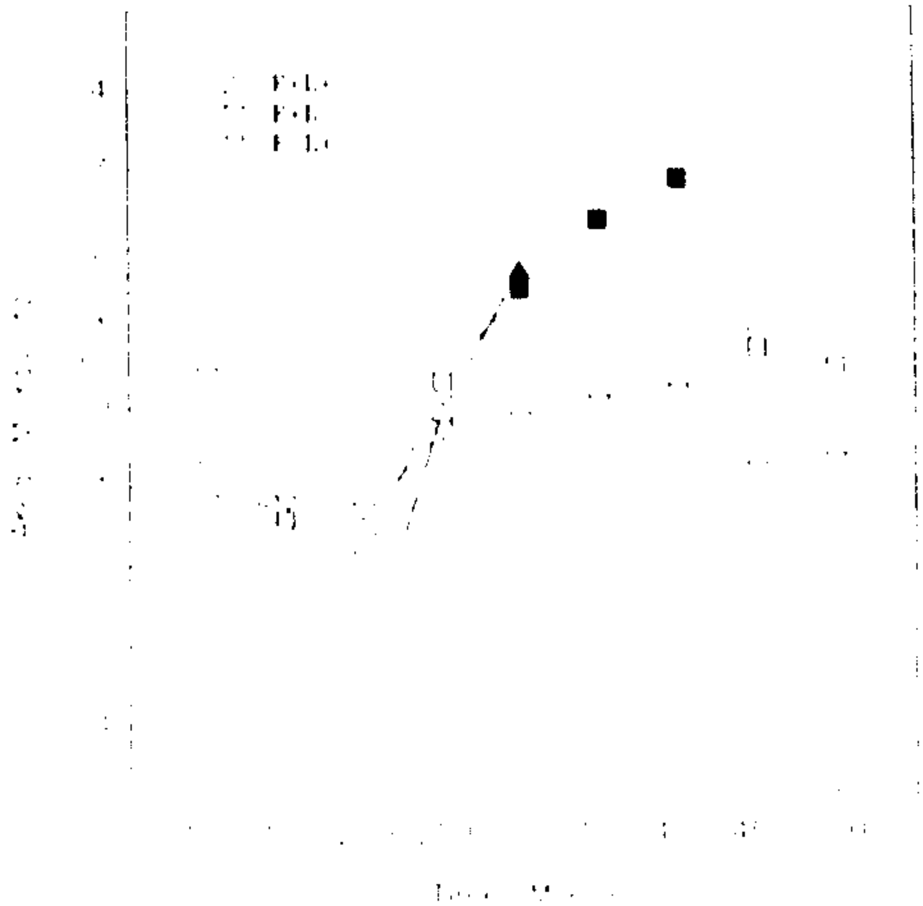

Figure A22: First Trial Analysis - Nd Area at Fz for Location Switch

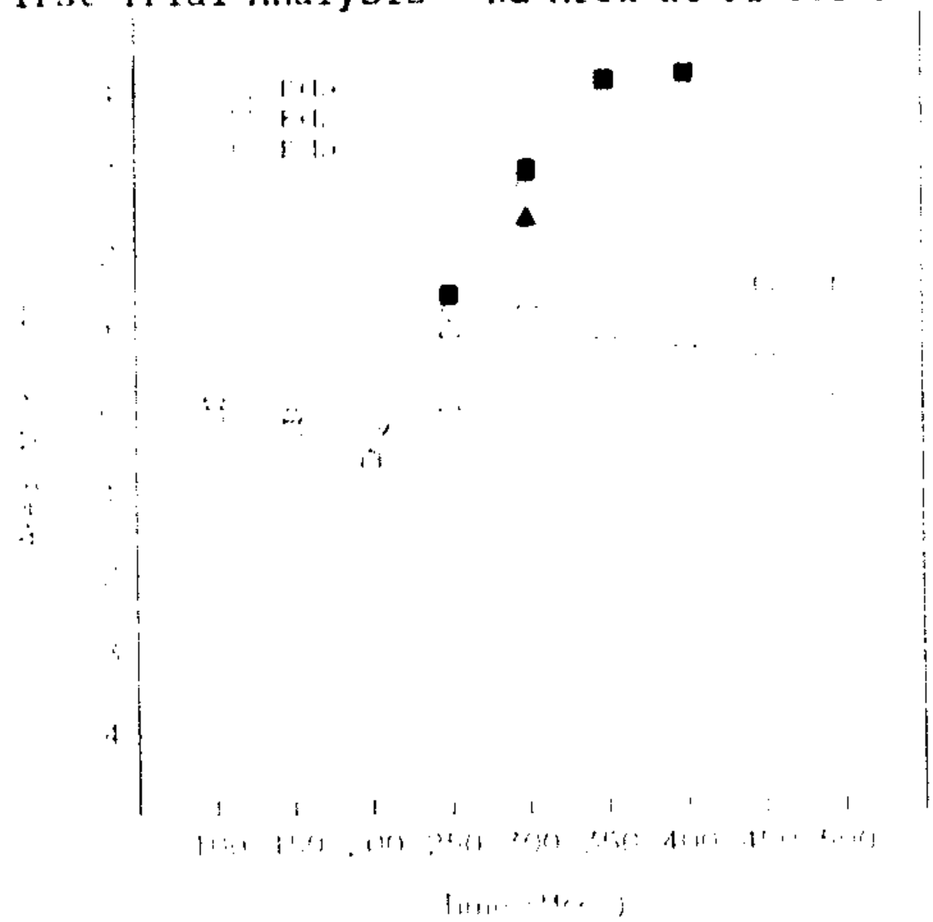

Figure A23: First Trial Analysis - Nd Area at Fz for No Switch

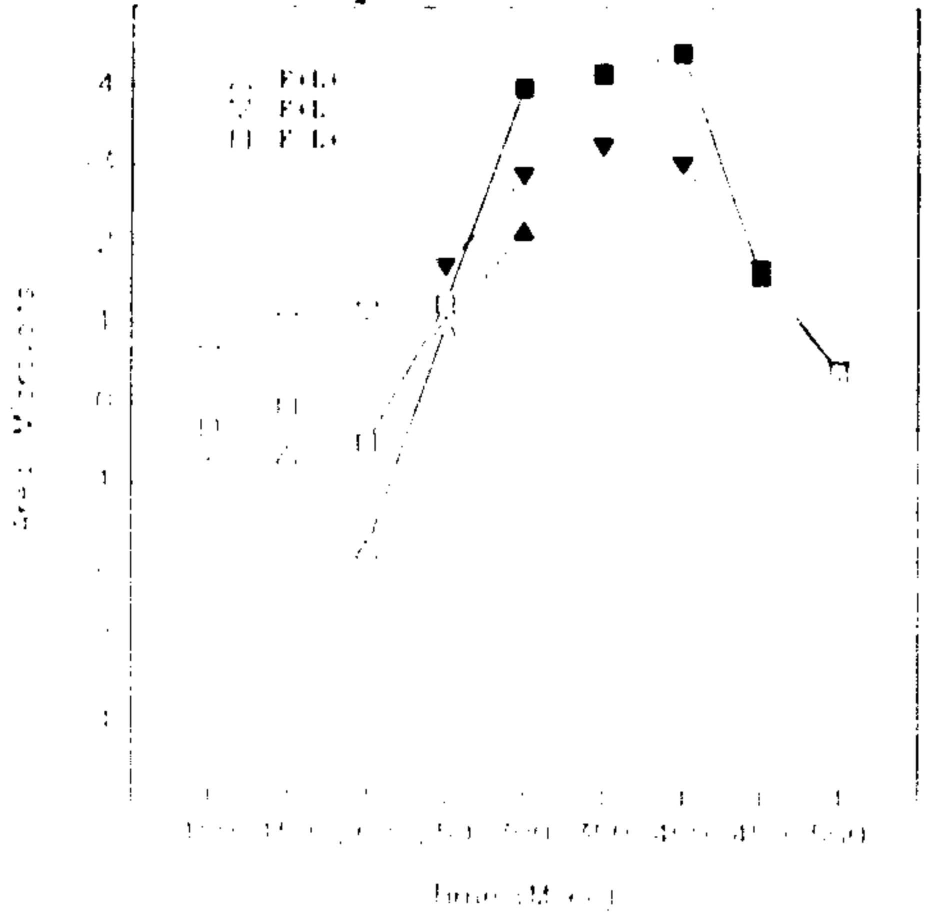

Figure A24: First Trial Analysis - Nd Area at Cz for Both Switch

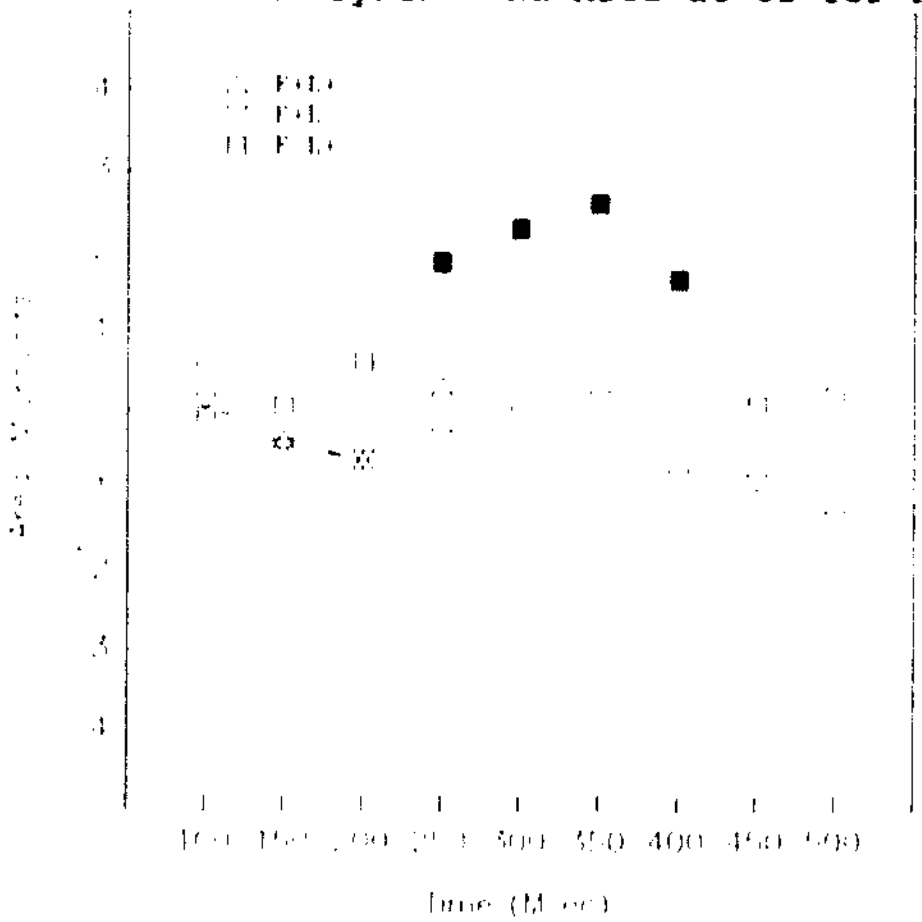

Figure A25: First Trial Analysis - Nd Area at Cz for Frequency Switch

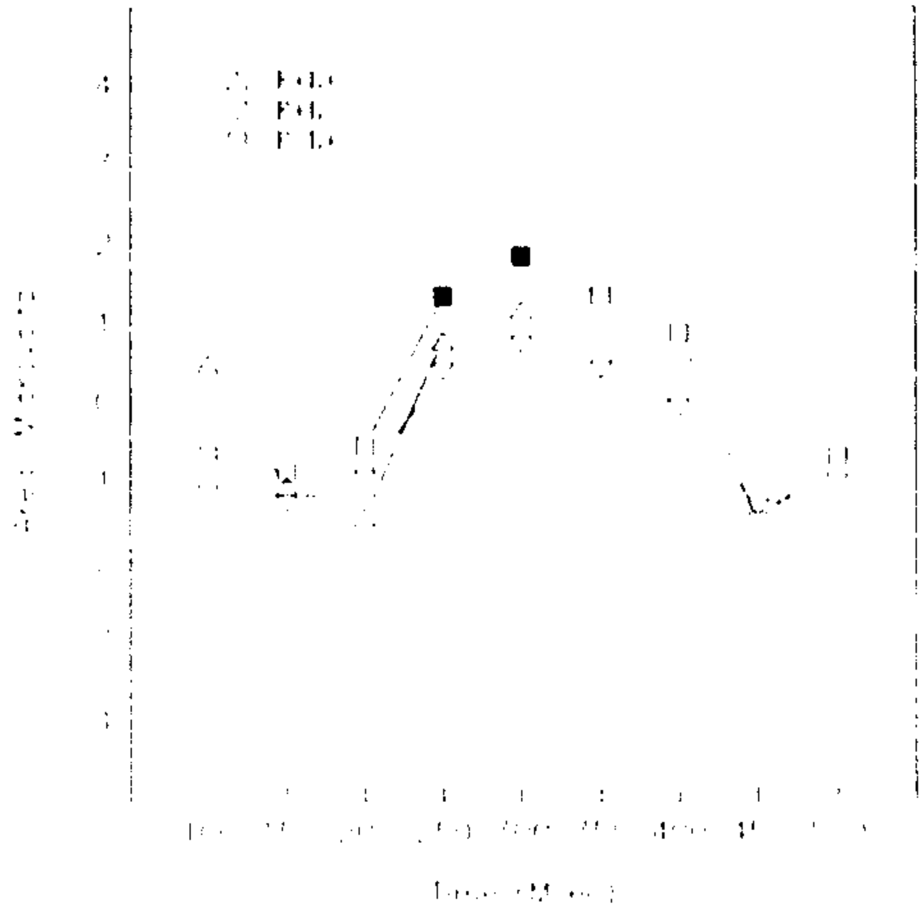

Figure A26: First Trial Analysis - Nd Area at Cz for Location Switch

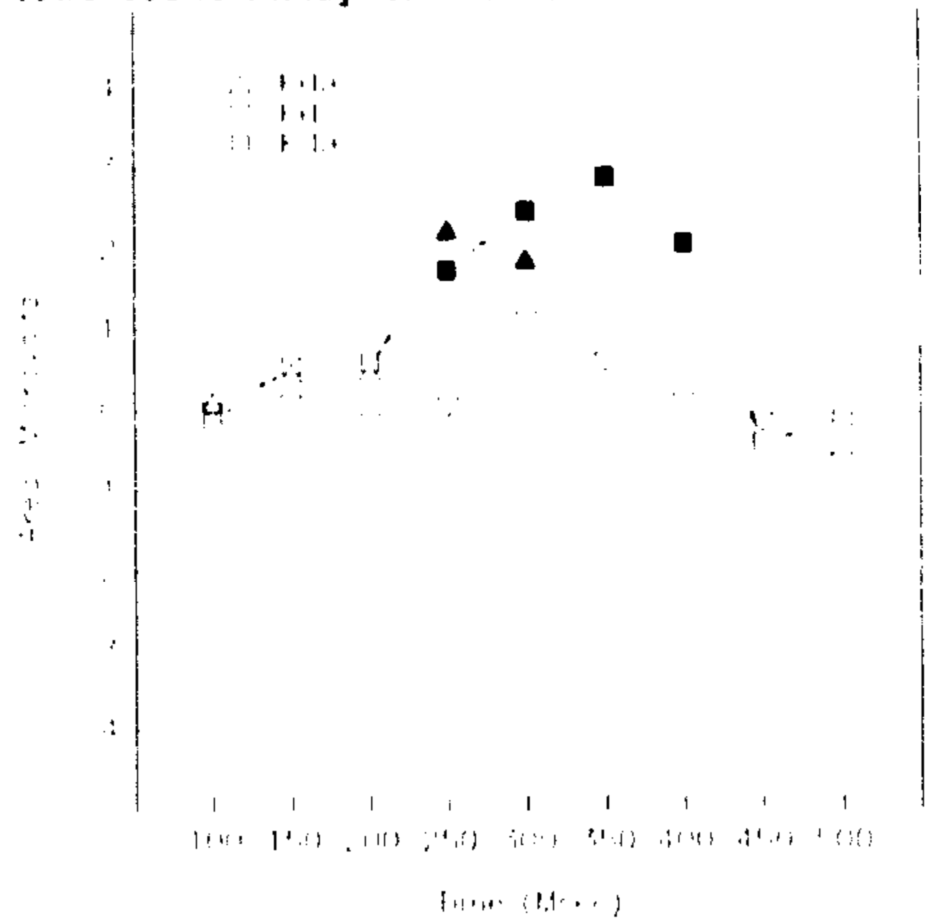

Figure A27: First Trial Analysis - Nd Area at Cz for No Switch

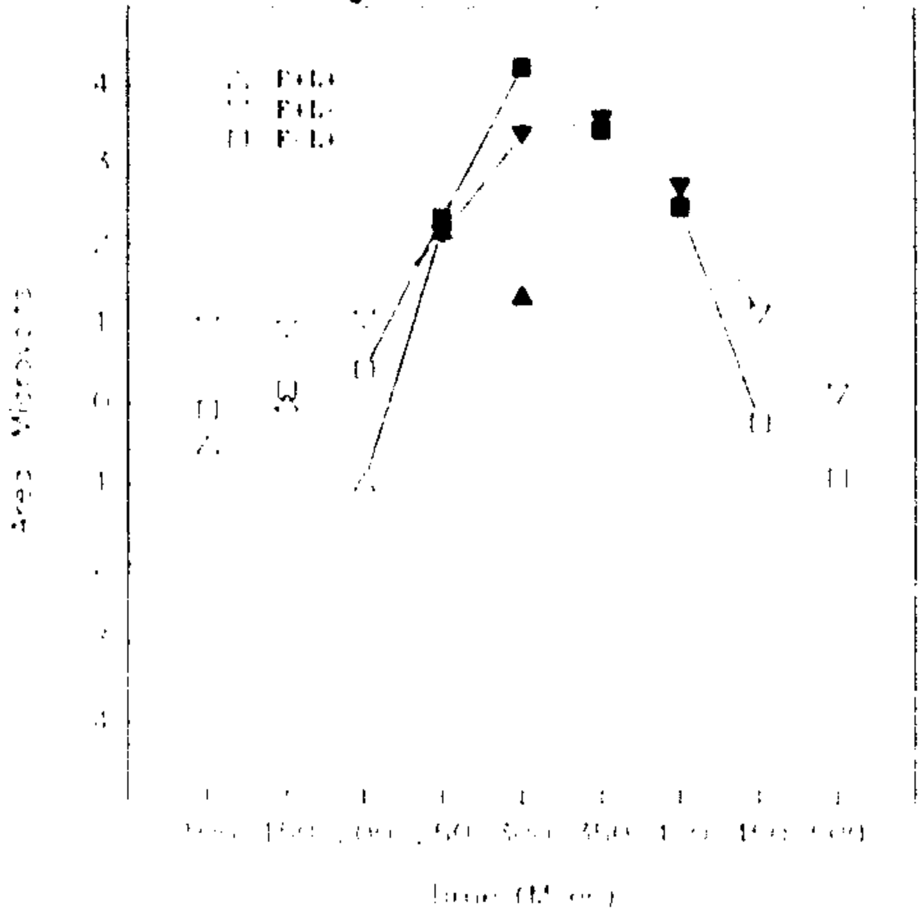

Figure A28: Sequential Position Analysis - Average ERPs at Fz for Both Switch Early

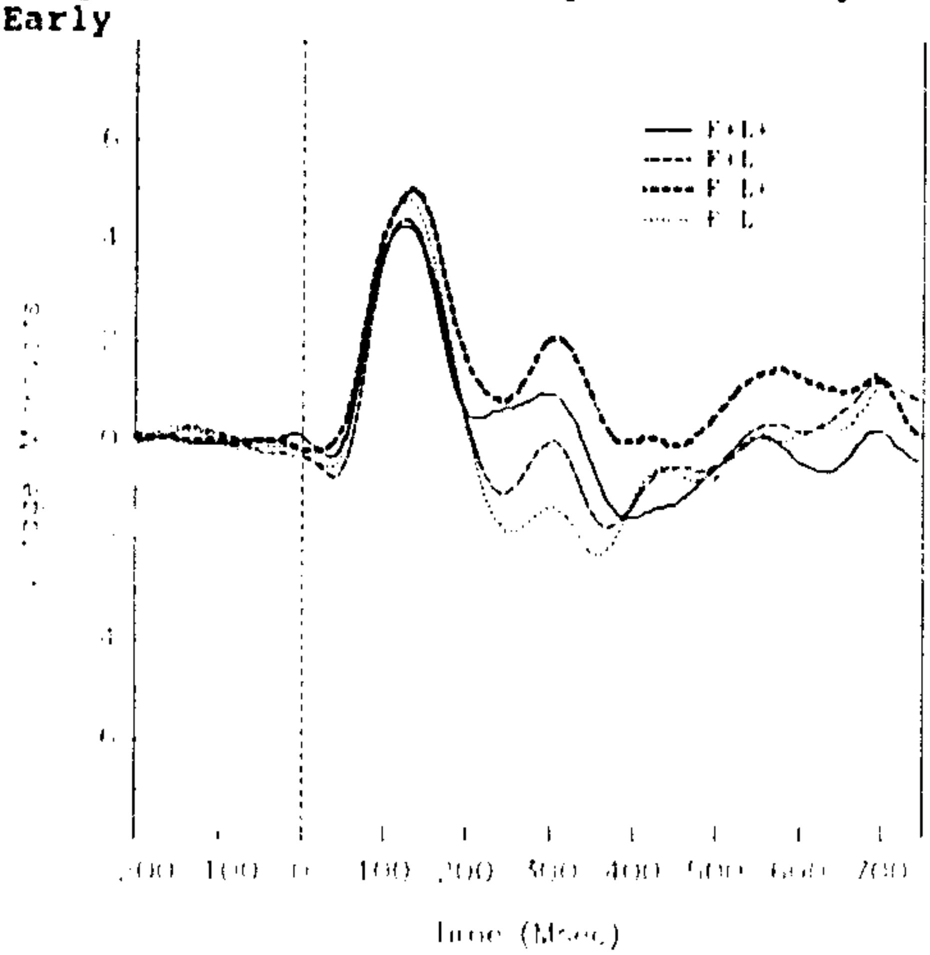

Figure A29: Sequential Position Analysis - Average ERPs at Fz for Both Switch Middle

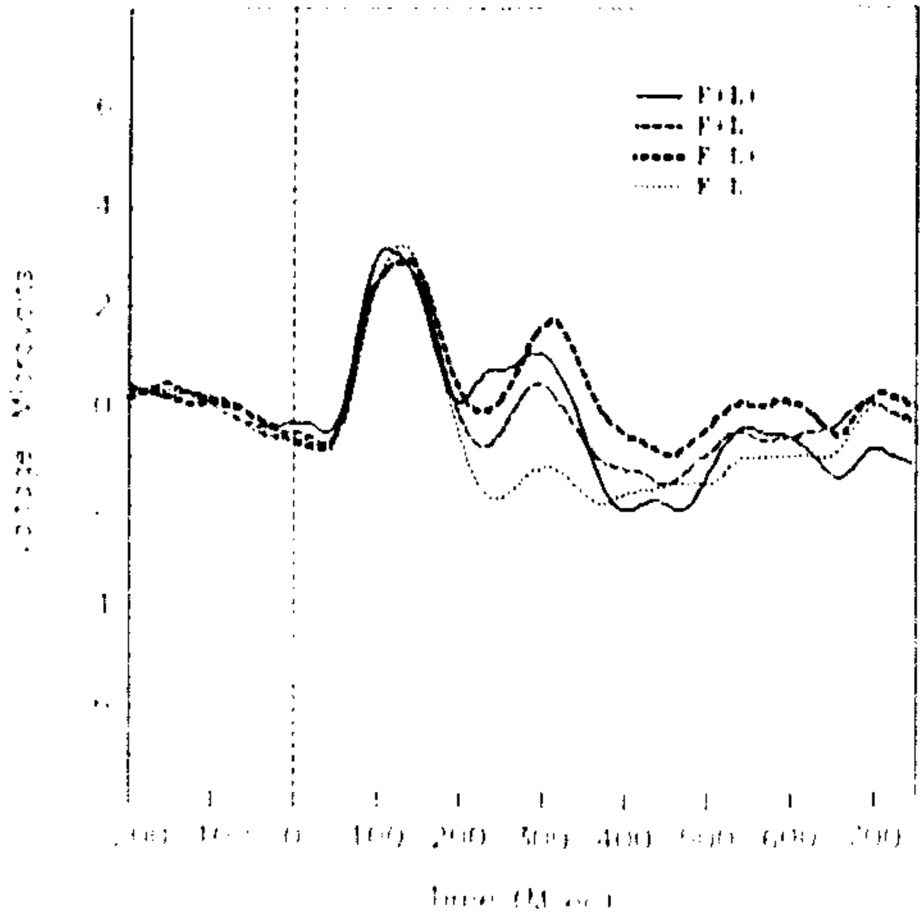

Figure A30: Sequential Position Analysis - Average ERPs at Fz for Both Switch Late

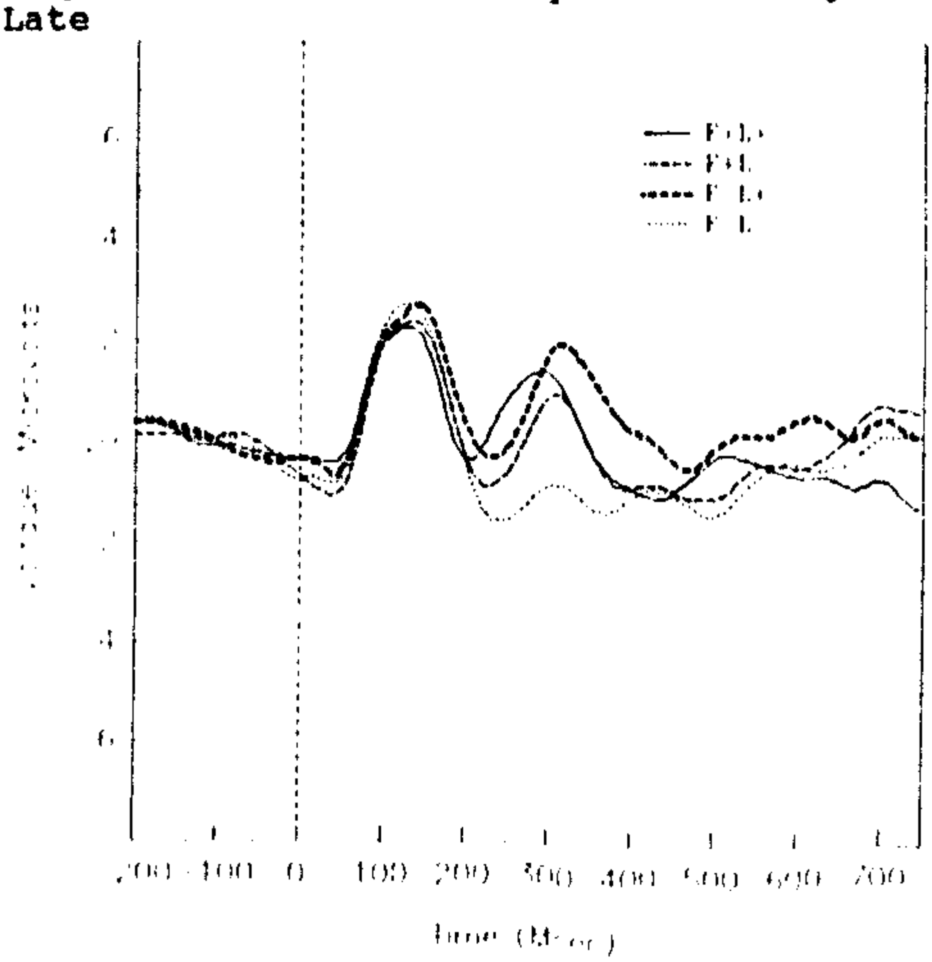

Figure A31: Sequential Position - Average ERPs at Fz for Frequency Switch Early

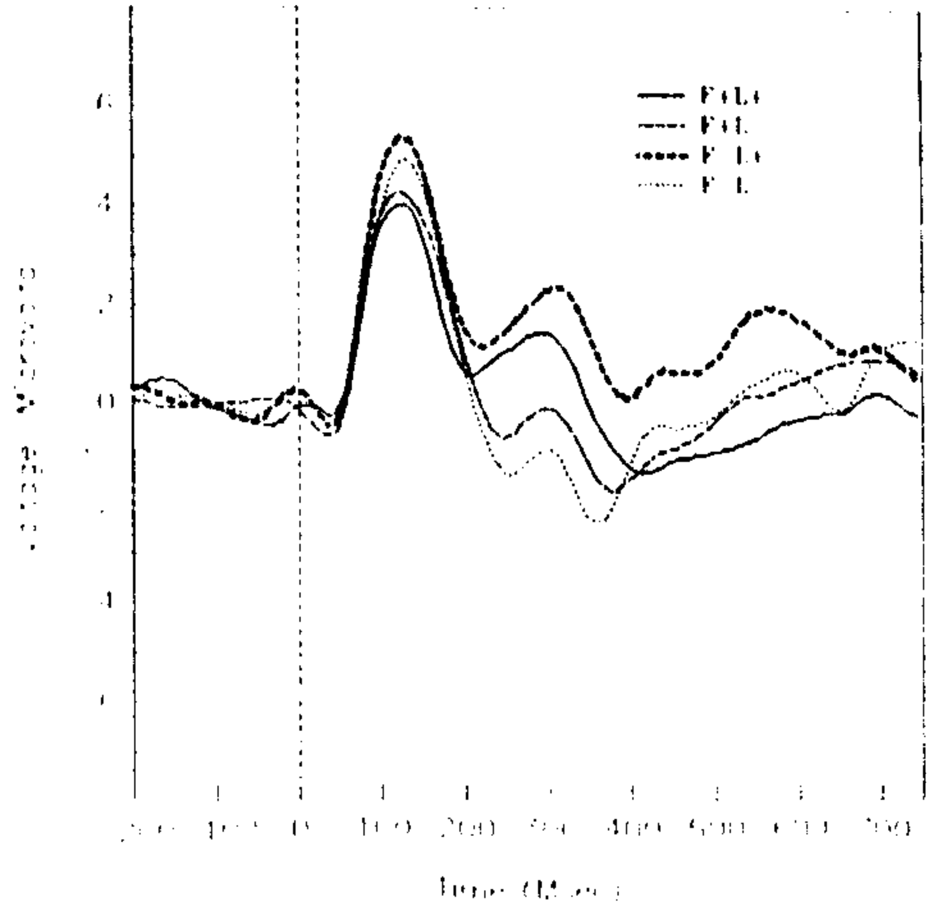

Figure A32: Sequential Position - Average ERPs at Fz for Frequency Switch Middle

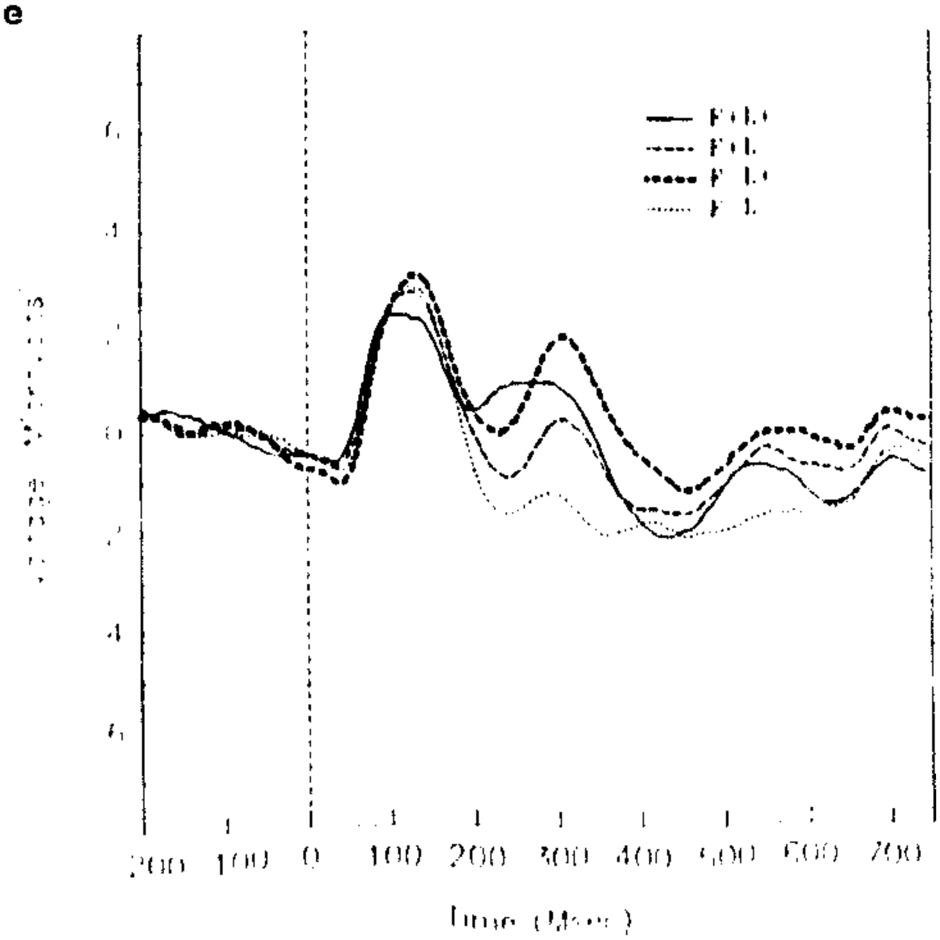

Figure A33: Sequential Position - Average ERPs at Fz for Frequency Switch Late

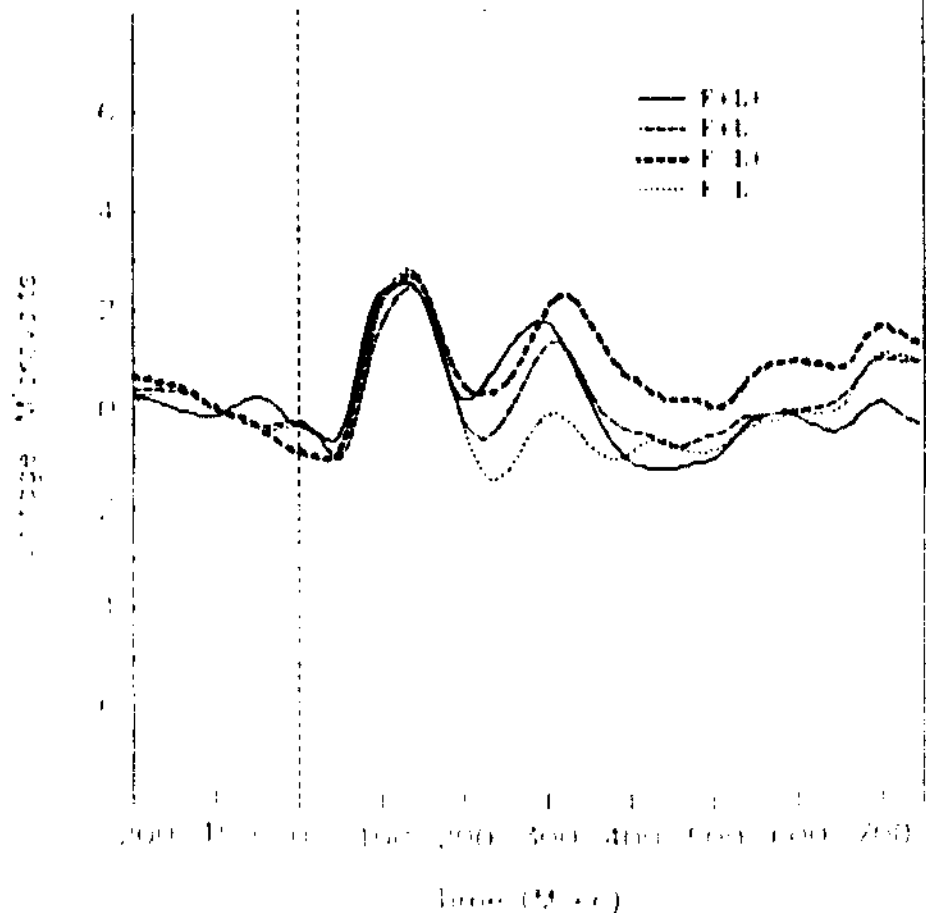

Figure A34: Sequential Position - Average ERPs at Fz for Location Switch Early

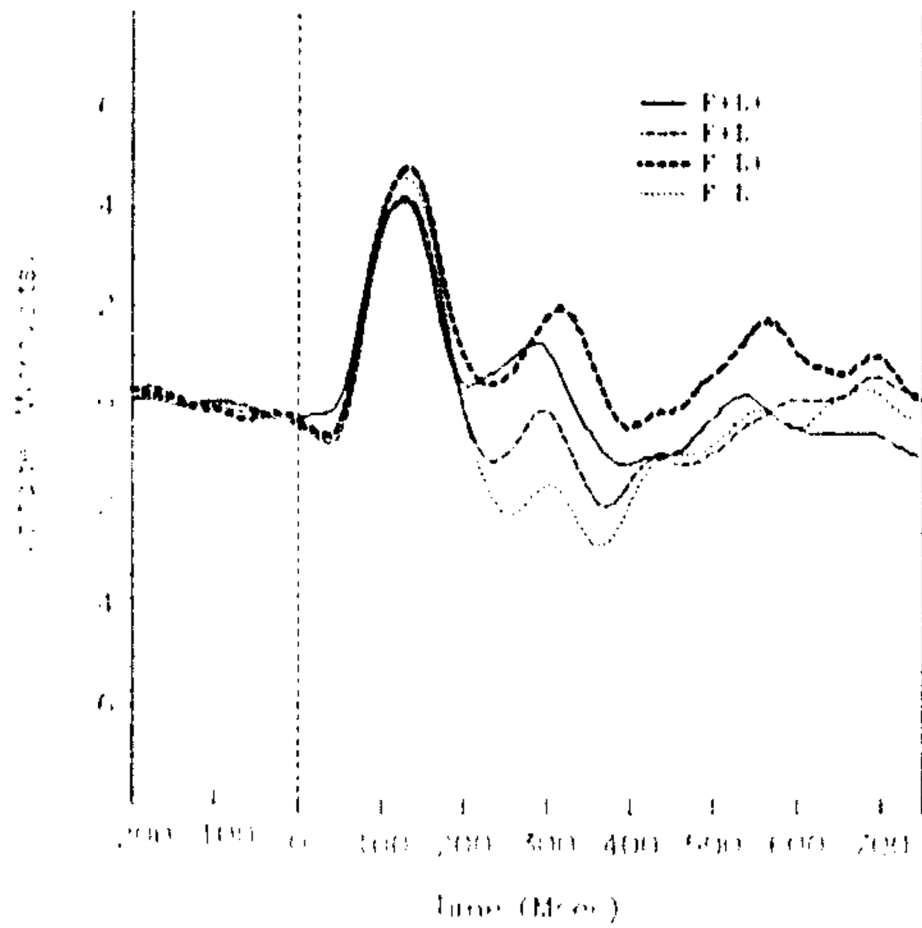

Figure A35: Sequential Position - Average ERPs at Fz for Location Switch Middle

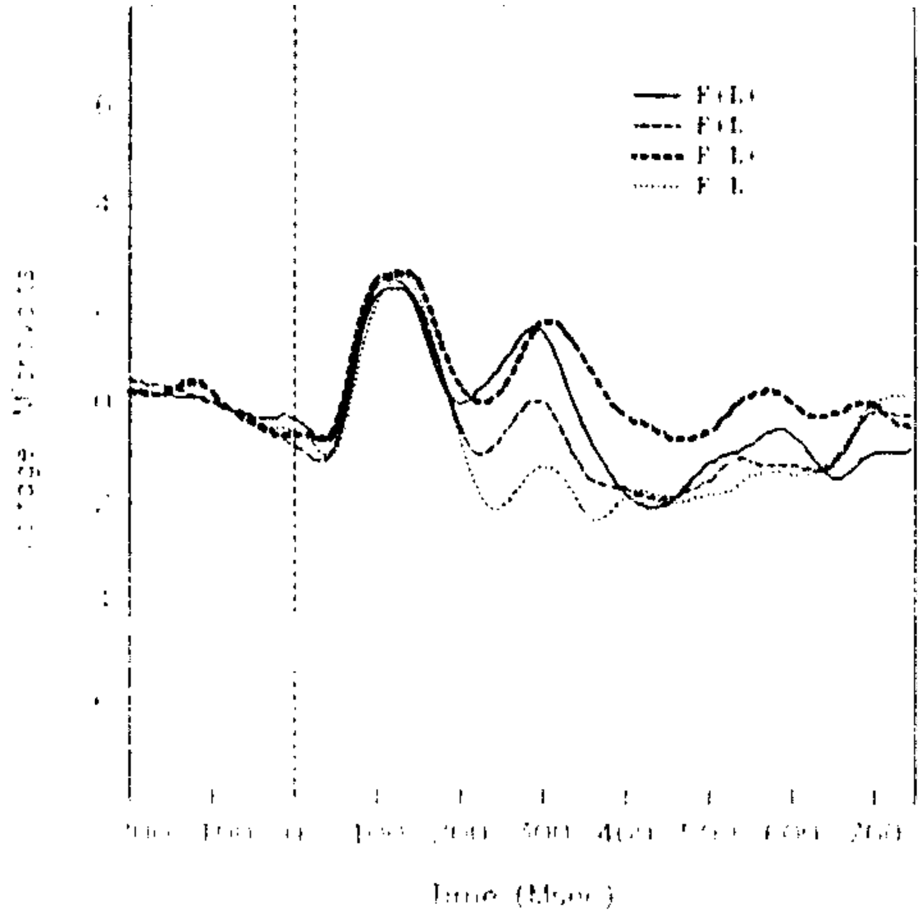

Figure A36: Sequential Position - Average ERPs at Fz for Location Switch Late

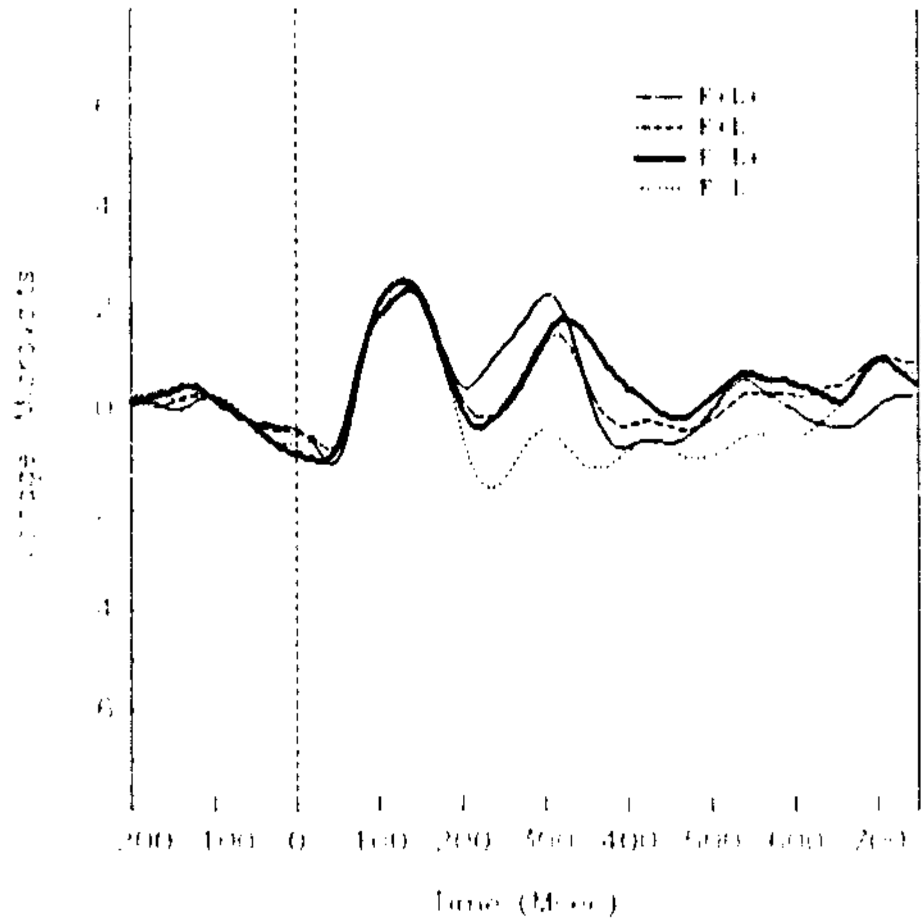

Figure A37: Sequential Position - Average ERPs at Fz for No Switch Early

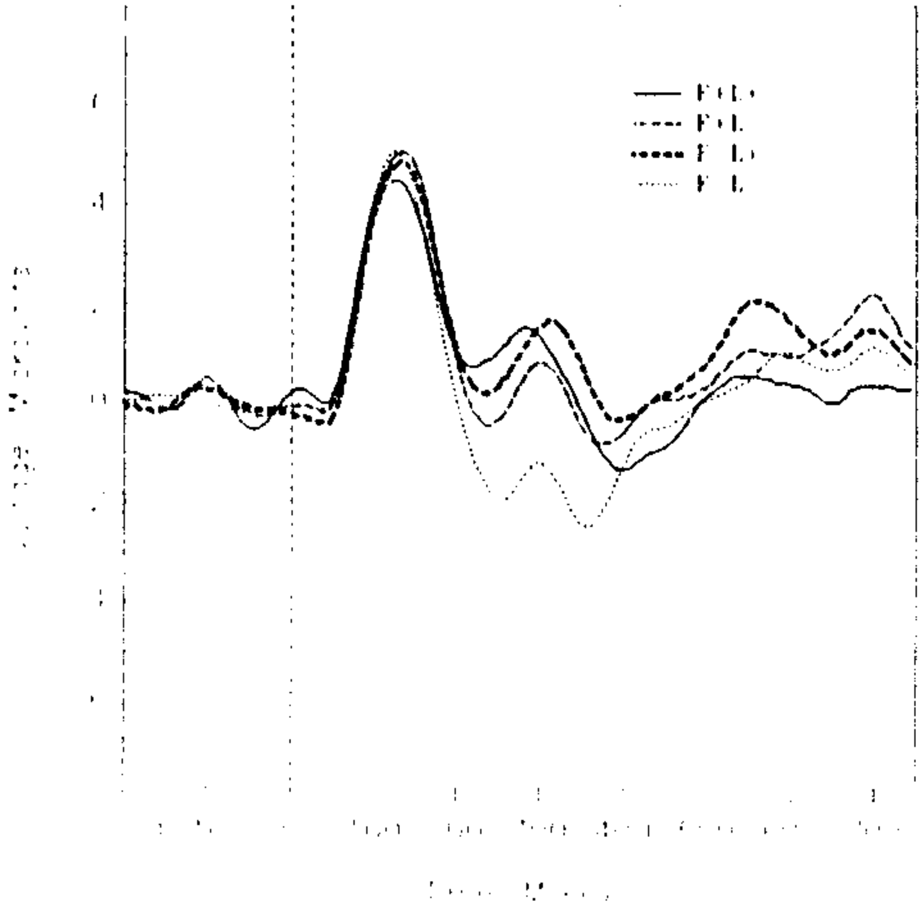

Figure A38: Sequential Position - Average ERPs at Fz for No Switch Middle

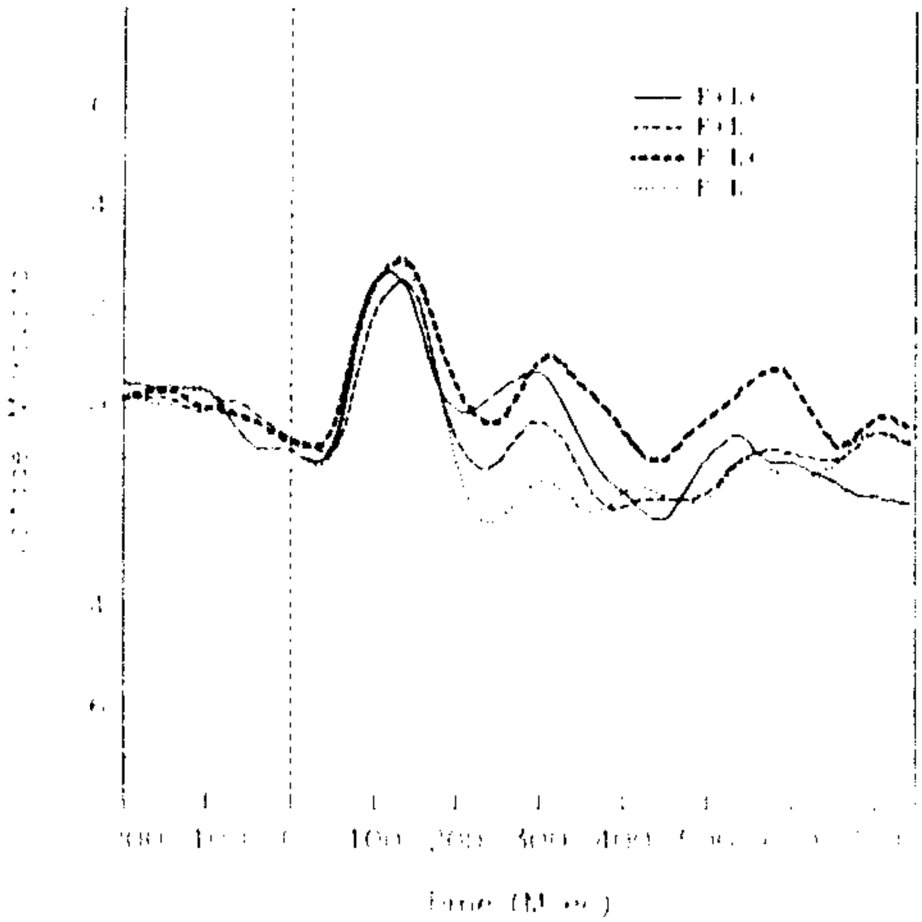

Figure A39: Sequential Position - Average ERPs at Fz for No Switch Late

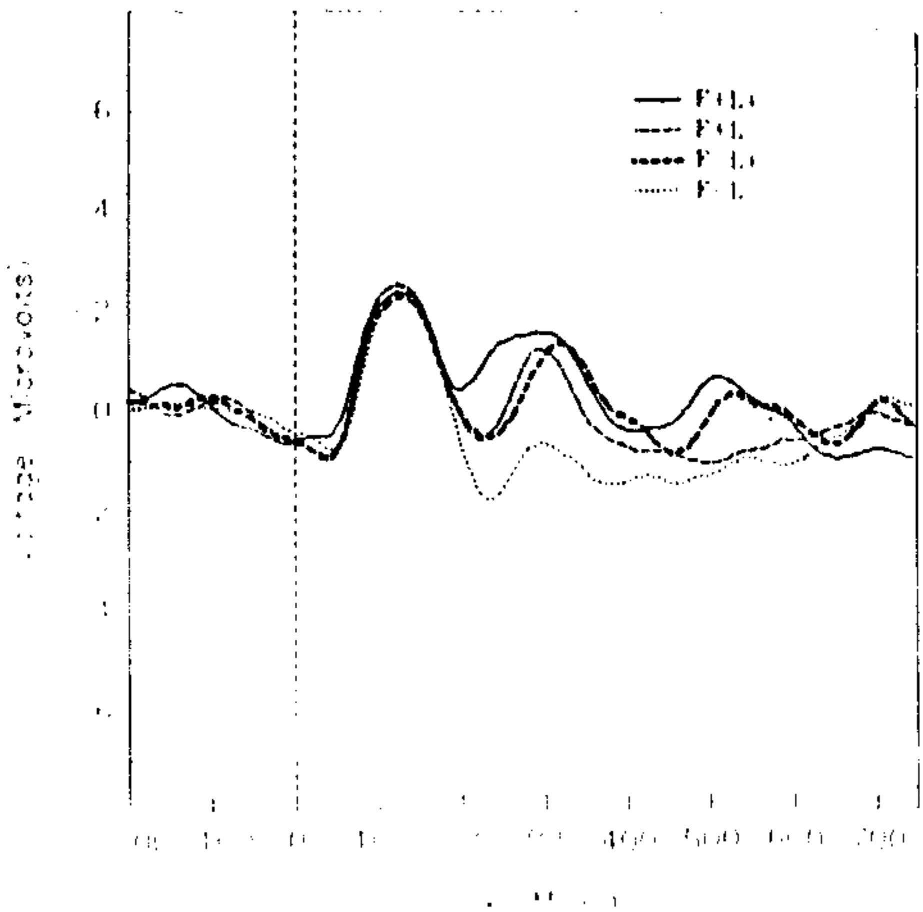

Figure A40: Sequential Position - Average ERPs at Cz for Both Switch Early

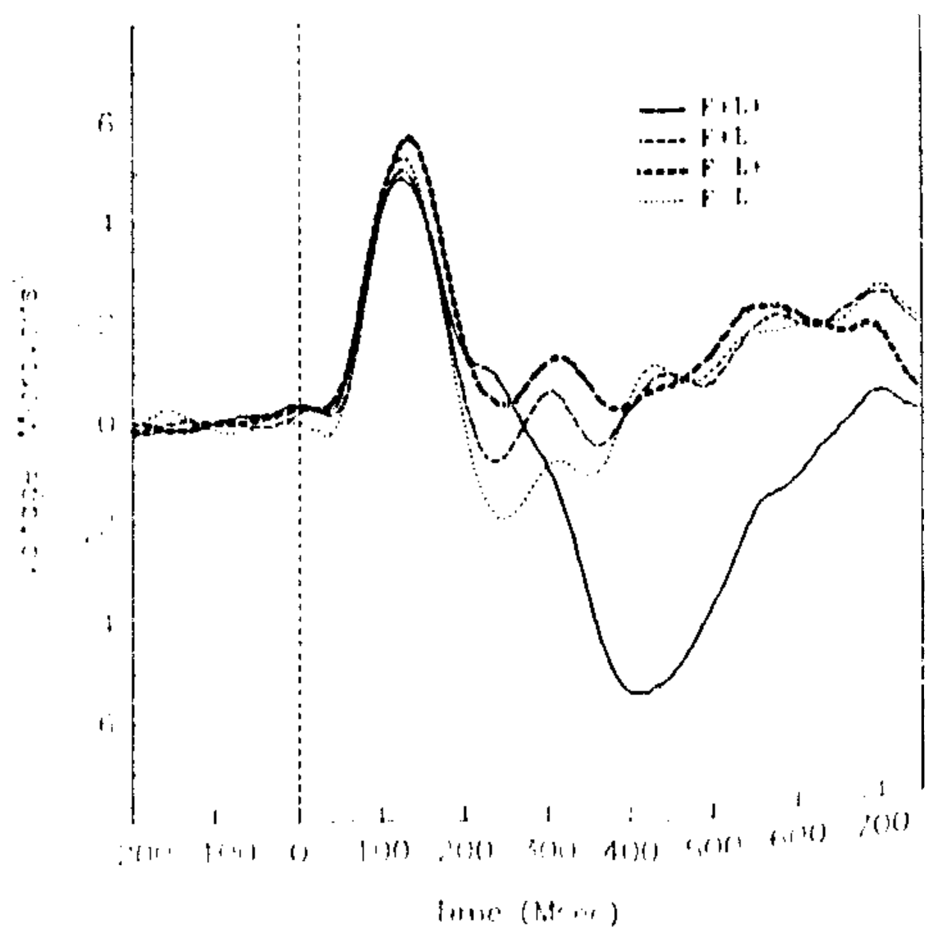

Figure A41: Sequential Position - Average ERPs at Cz for Both Switch Middle

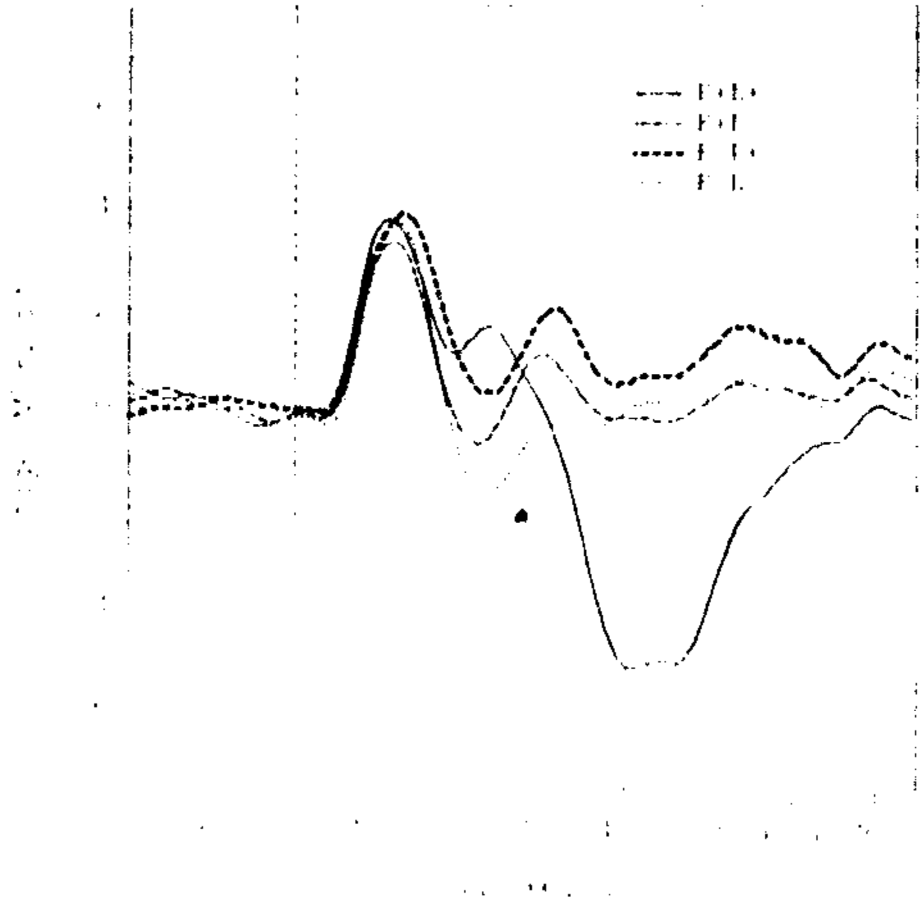

Figure A42: Sequential Position - Average ERPs at Cz for Both Switch Late

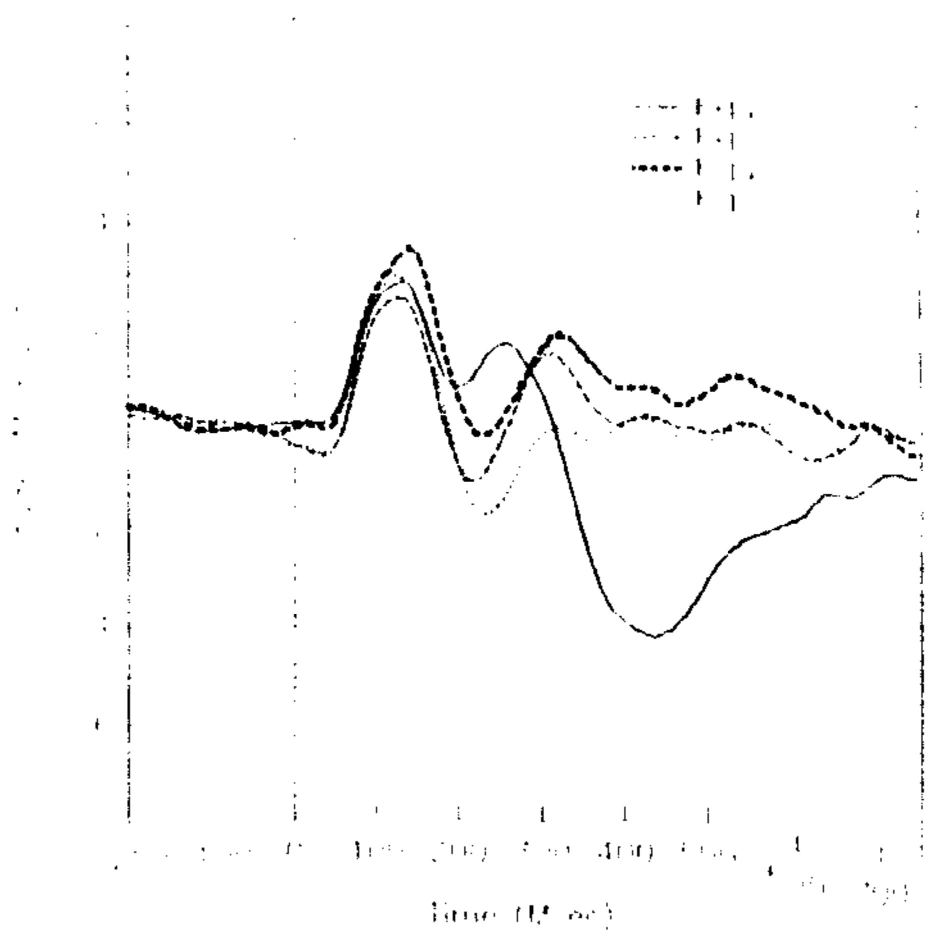

Figure A43: Sequential Position - Average ERPs at Cz for Frequency Switch Early

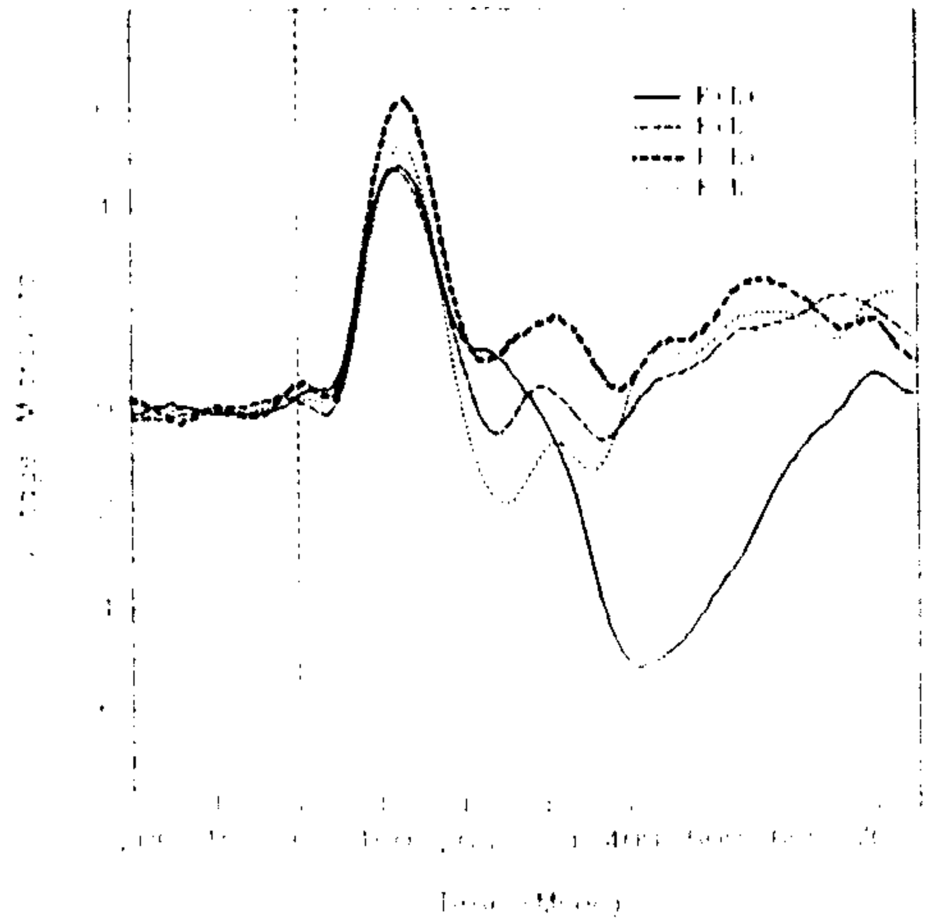

Figure A44: Sequential Position - Average ERPs at Cz for Frequency Switch Middle

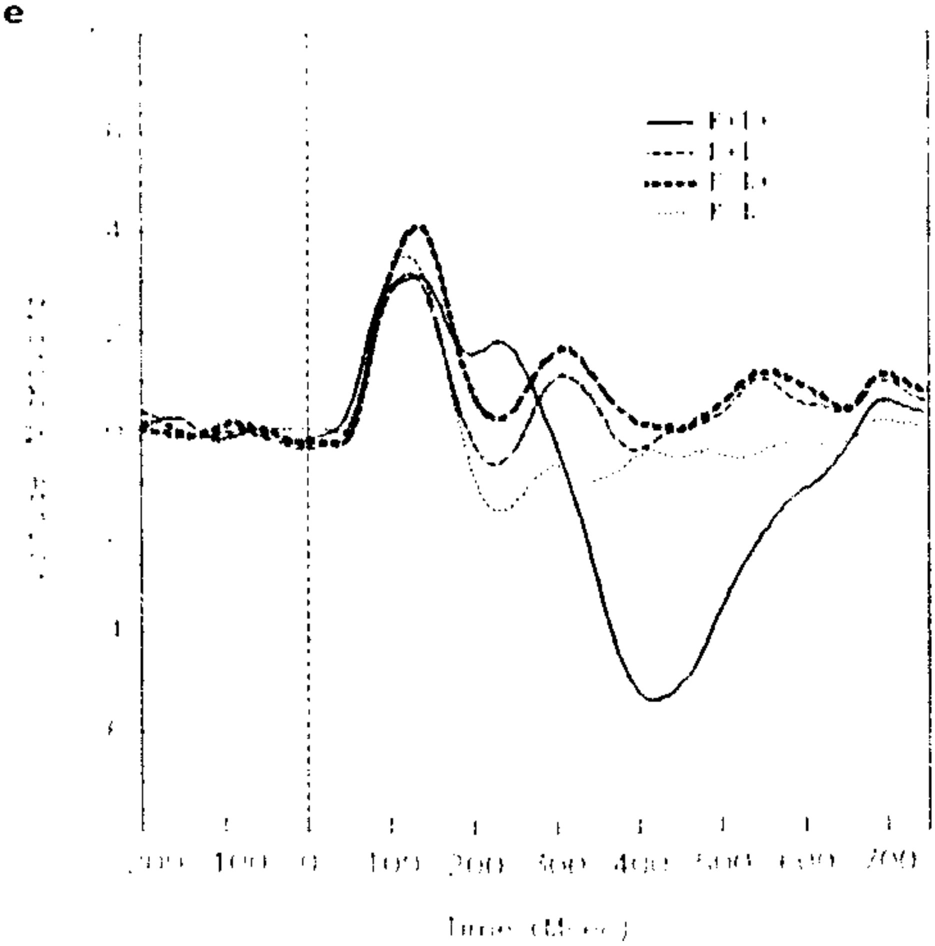

Figure A45: Sequential Position - Average ERPs at Cz for Frequency Switch Late

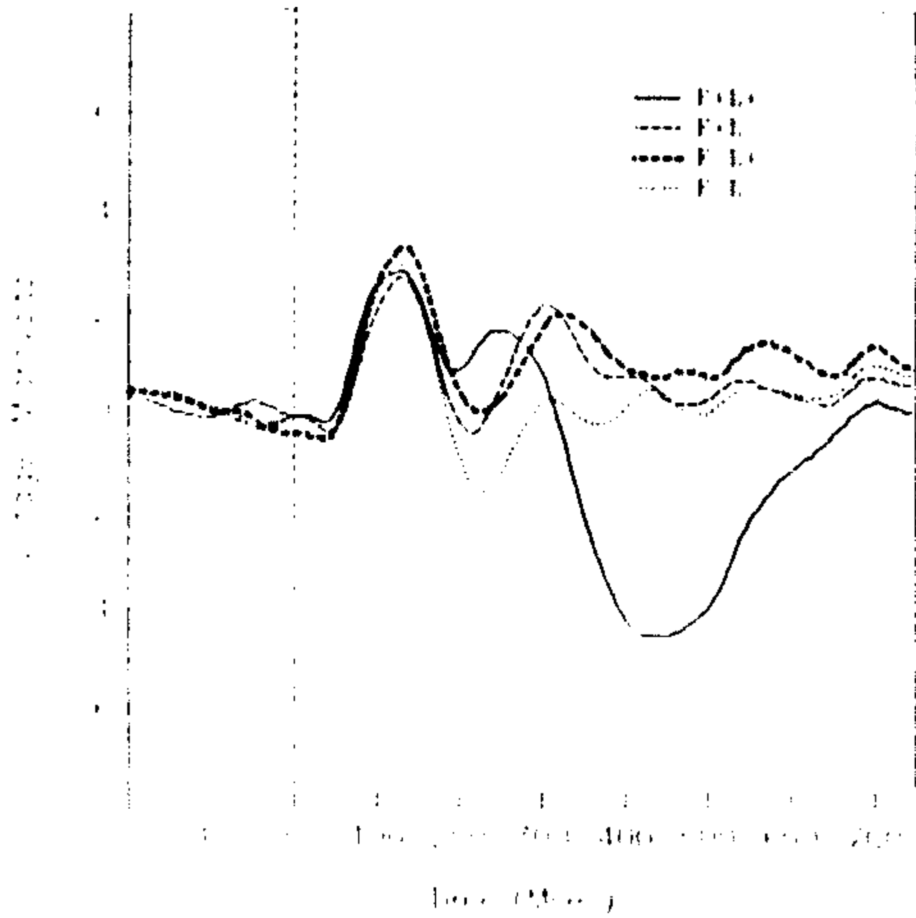

Figure A46: Sequential Position - Average ERPs at Cz for No Switch Early

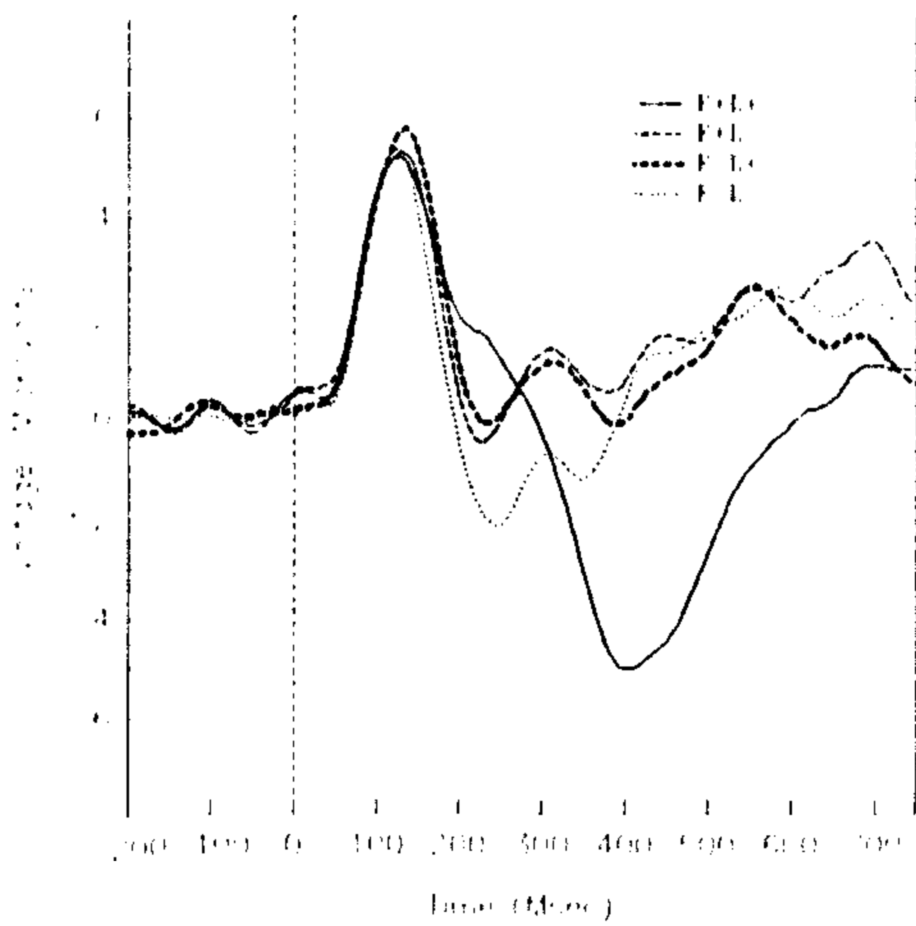

Figure A47: Sequential Position - Average ERPs at Cz for No Switch Middle

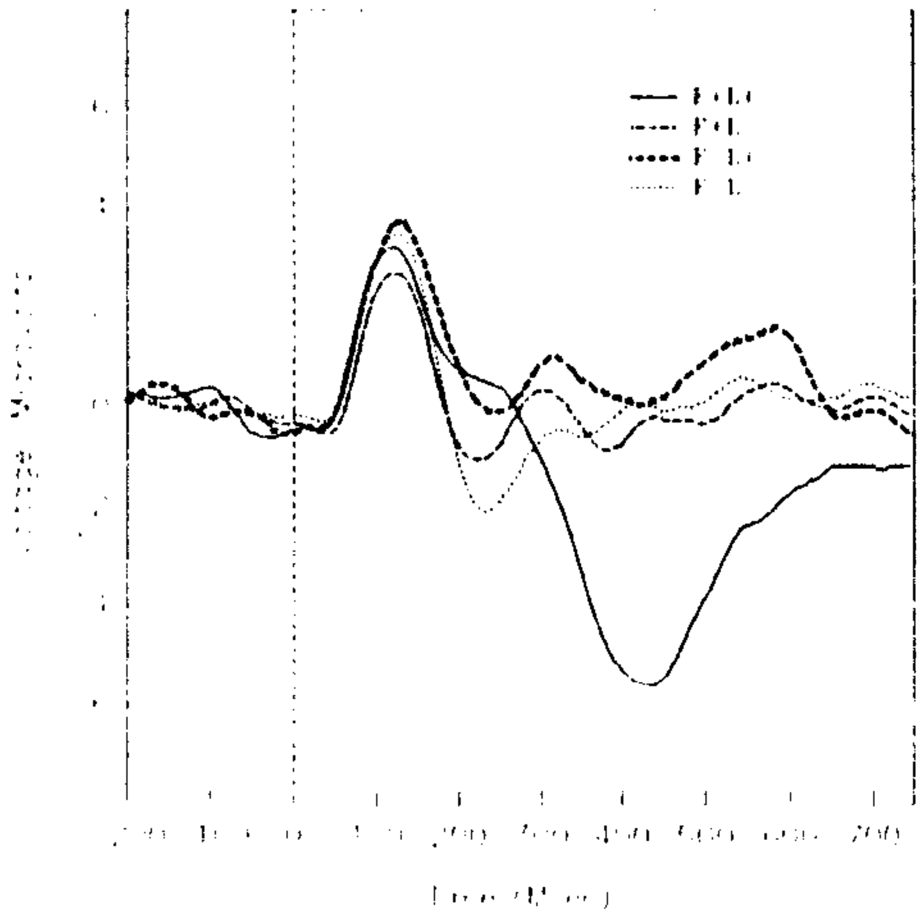

Figure A48: Sequential Position - Average ERPs at Cz for No Switch Late

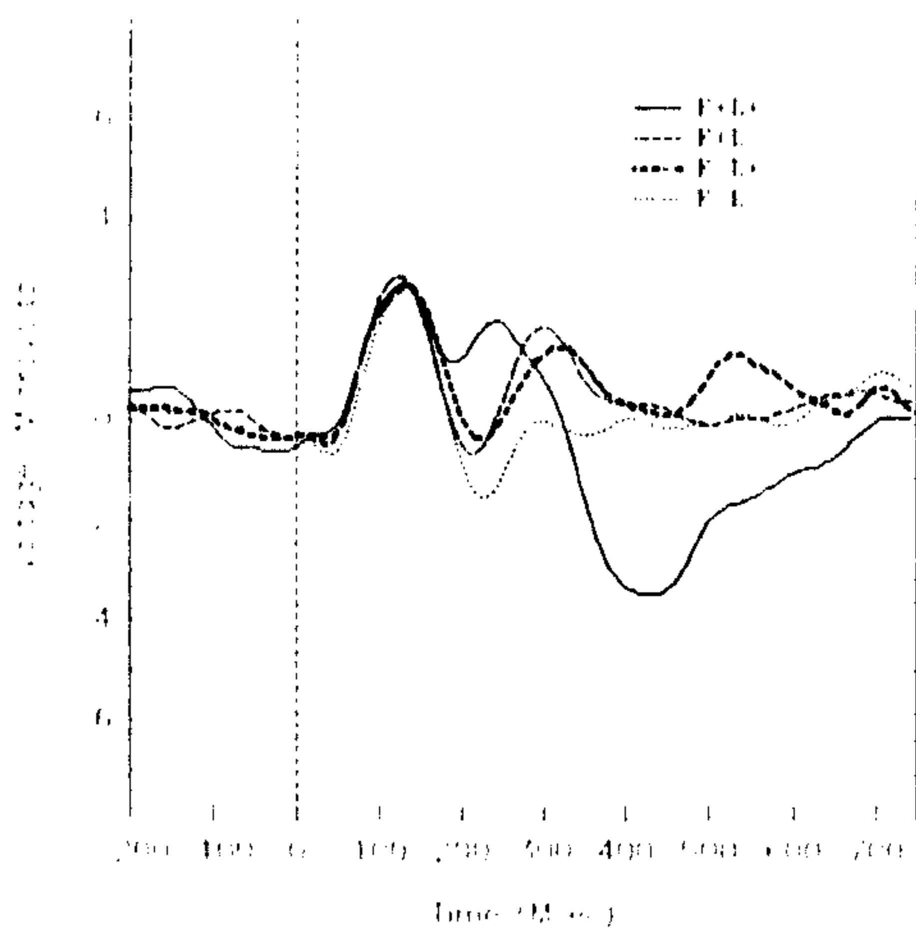

Figure A49: Sequential Position - Average ERPs at Pz for Both Switch Early

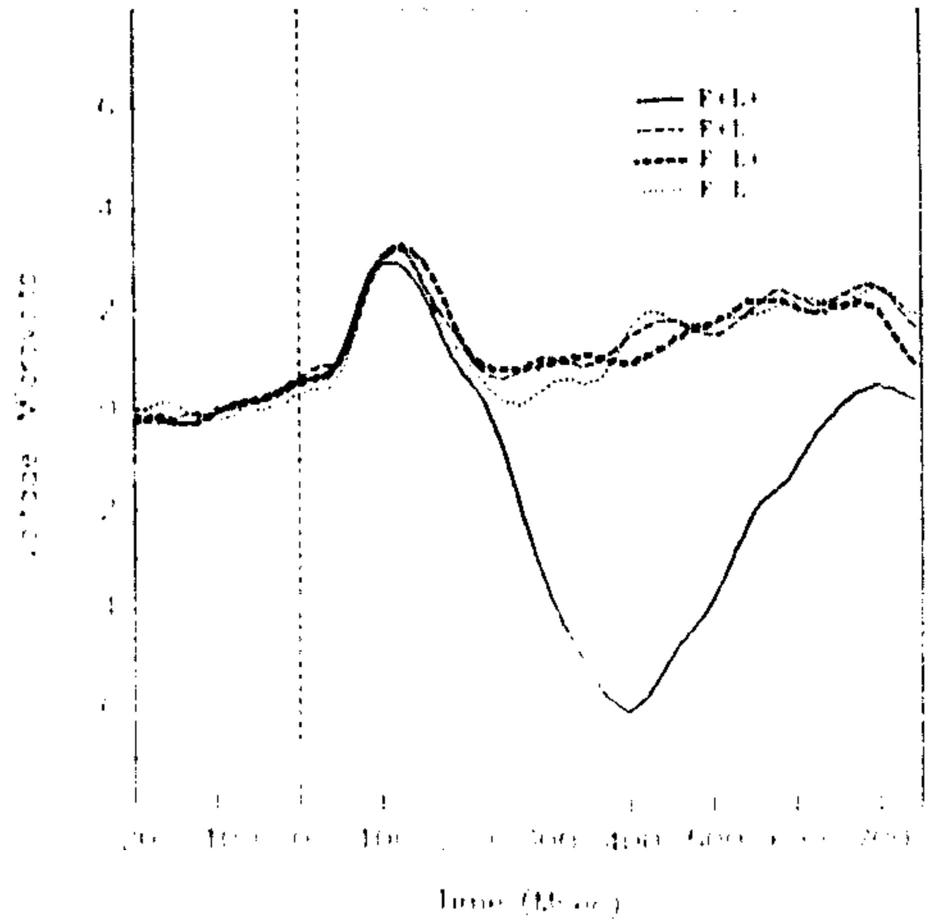

Figure A50: Sequential Position - Average ERPs at Pz for Both Switch Middle

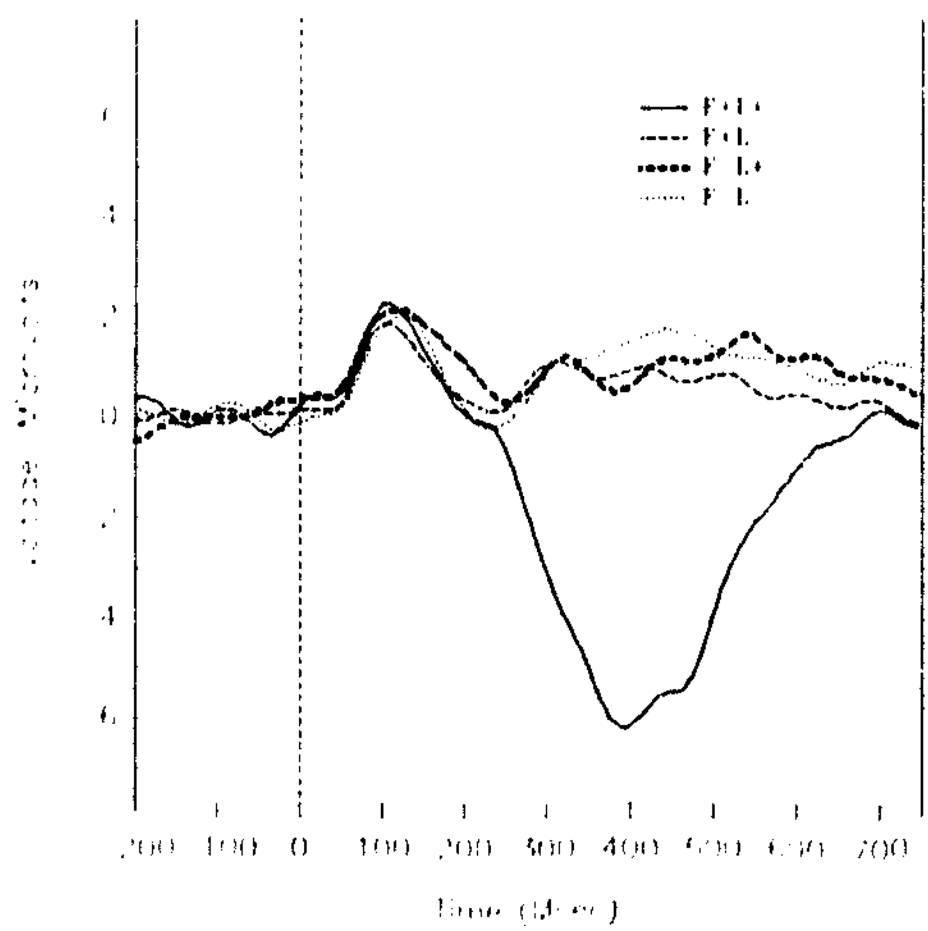

Figure A51: Sequential Position - Average ERPs at Pz for Both Switch Late

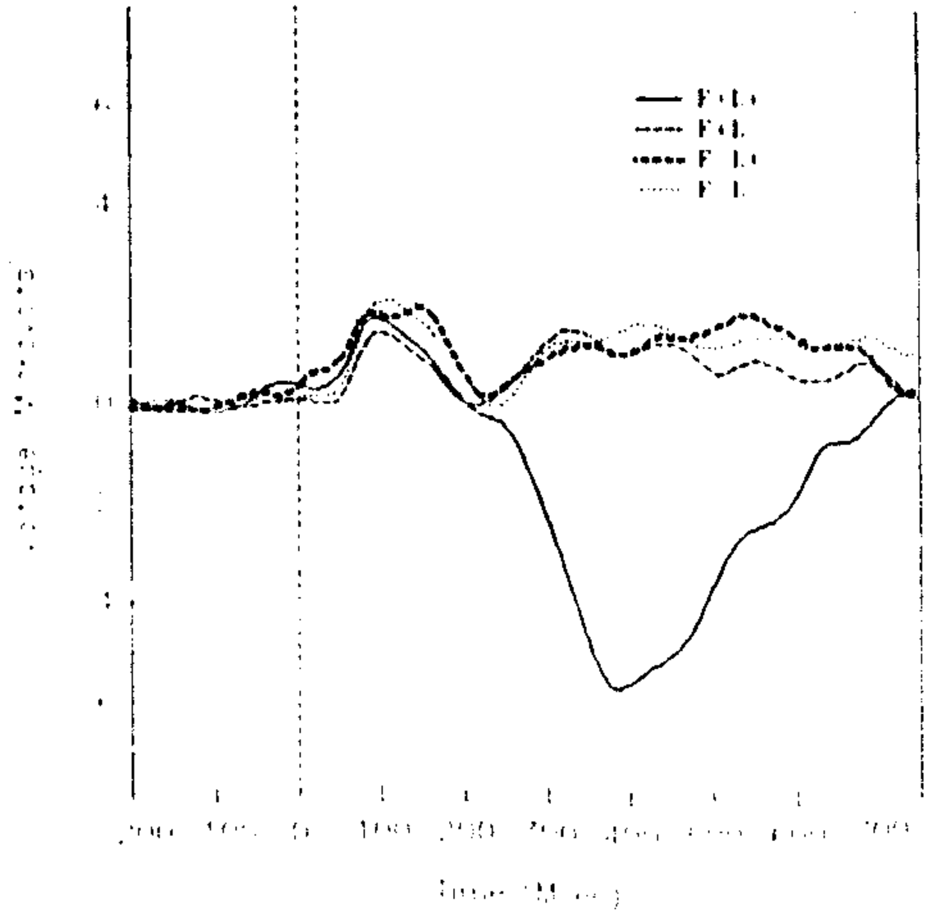

Figure A52: Sequential Position - Average ERPs at Pz for Frequency Switch Early

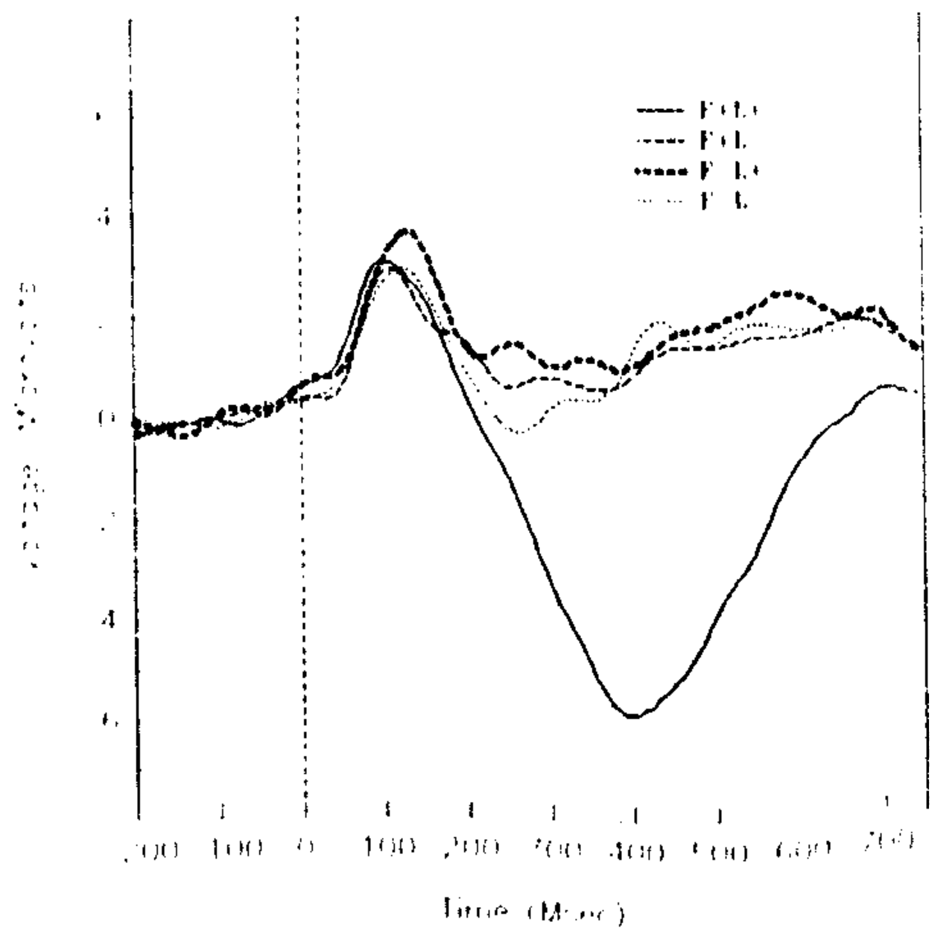

Figure A53: Sequential Position - Average ERPs at Pz for Frequency Switch Middle

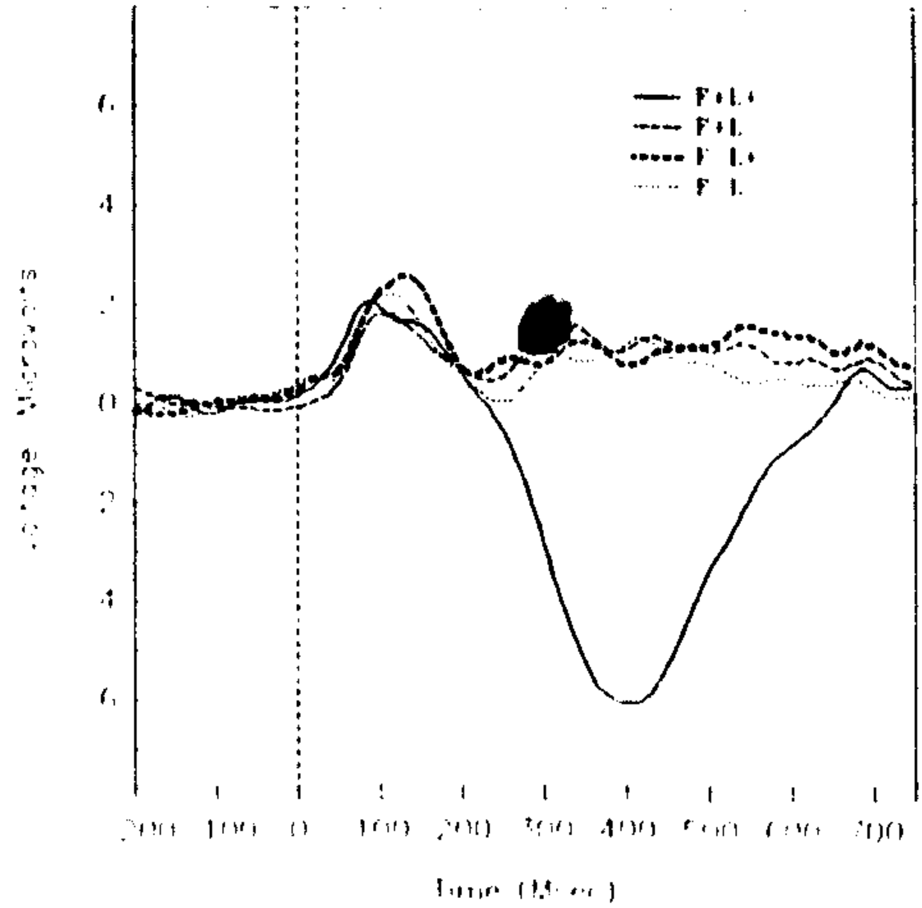

Figure A54: Sequential Position - Average ERPs at Pz for Frequency Switch Late

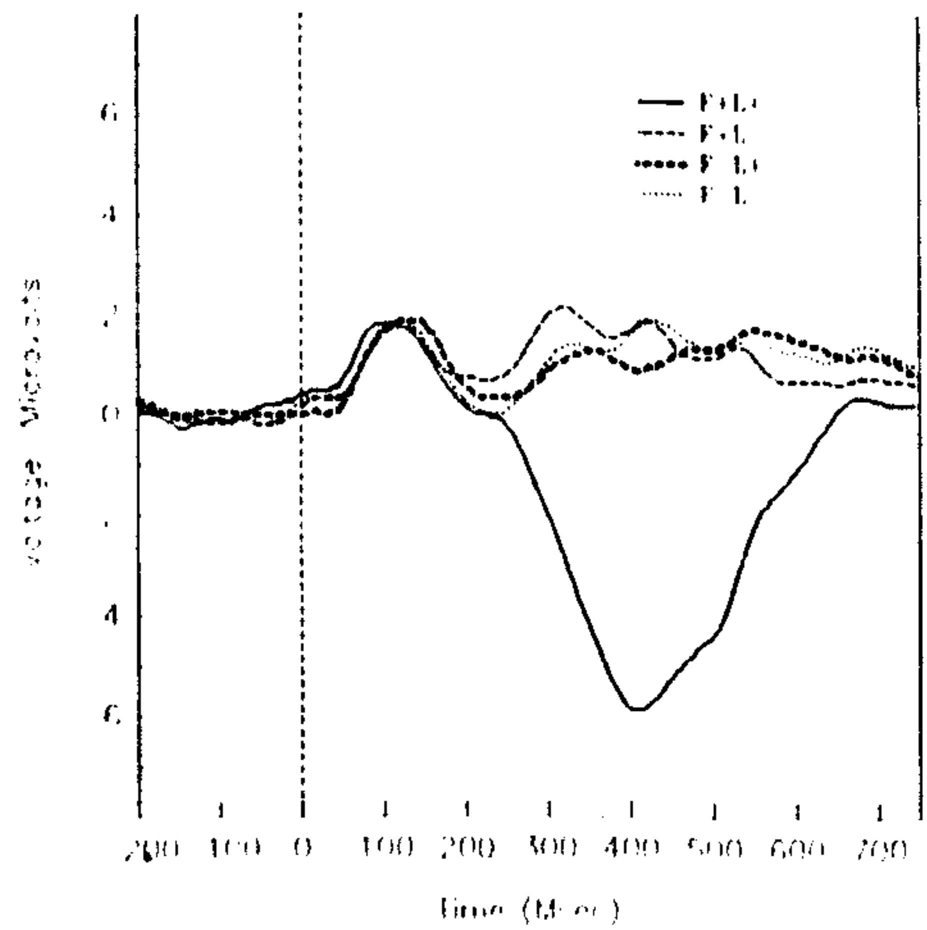

Figure A55: Sequential Position - Average ERPs at Pz for Location Switch Early

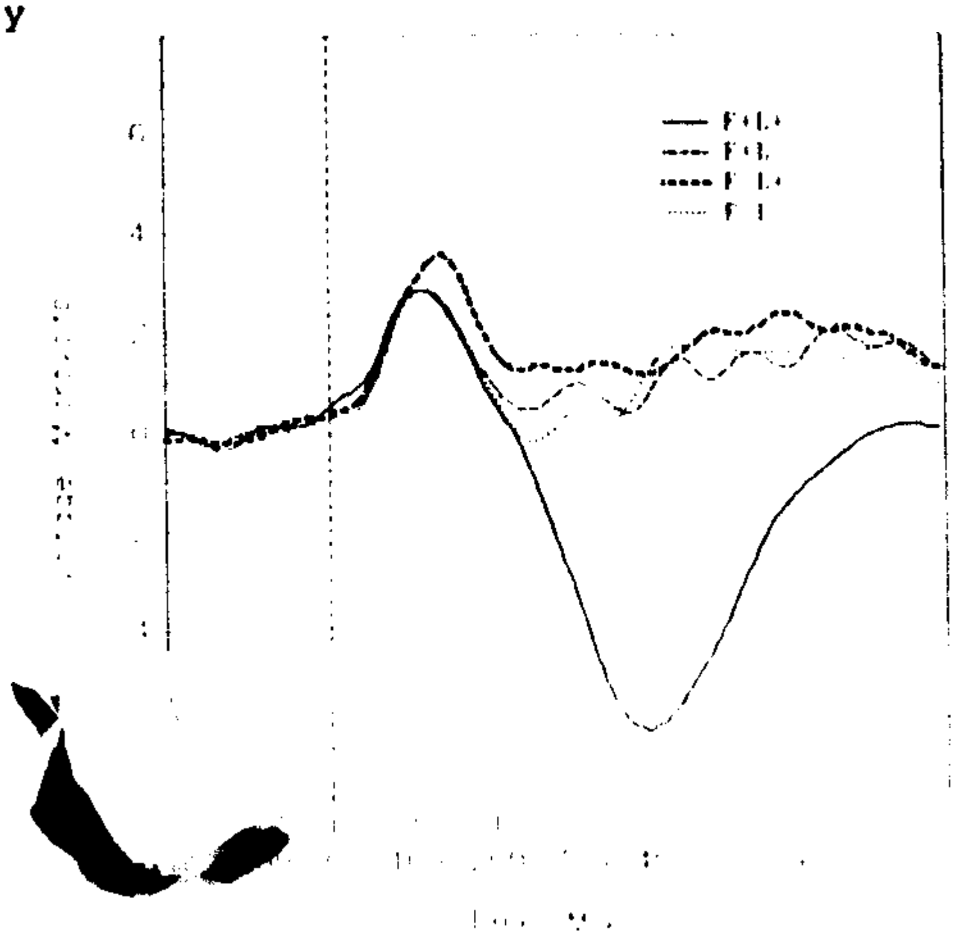

Figure A56: Sequential Position - Average ERPs at Pz for Location Switch Middle

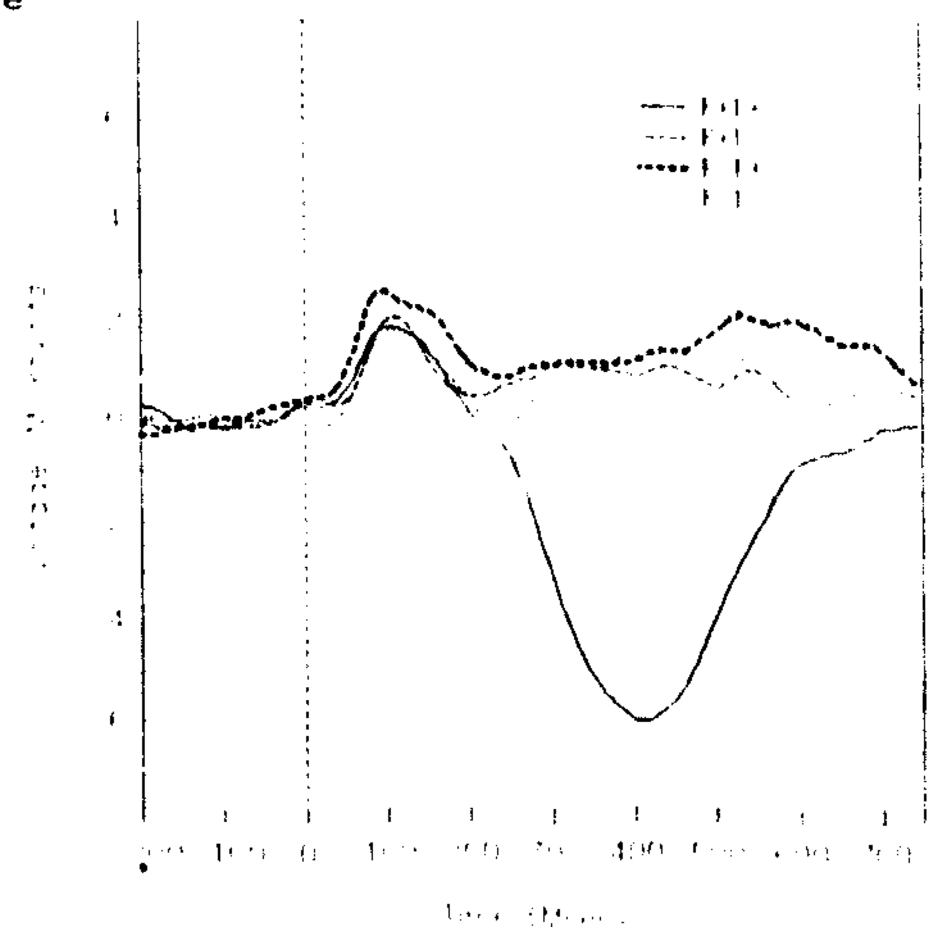

Figure A57: Sequential Position - Average ERPs at Pz for Location Switch Late

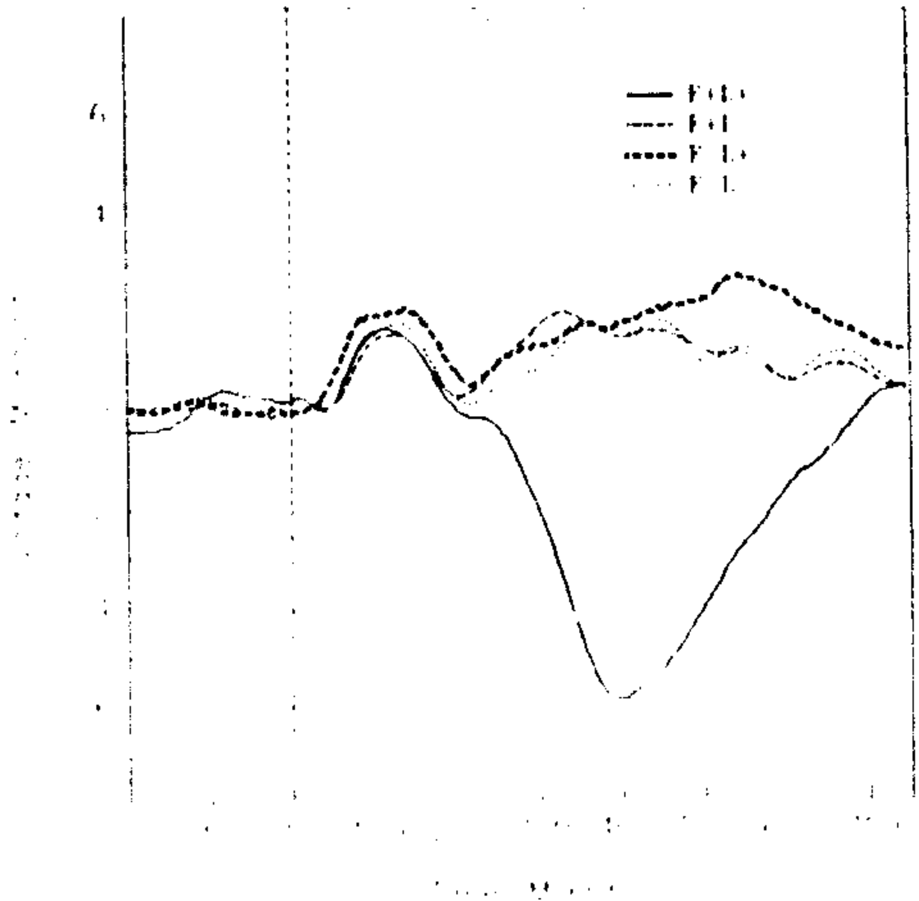

Figure A58: Sequential Position - Average ERPs at Pz for No Switch Early

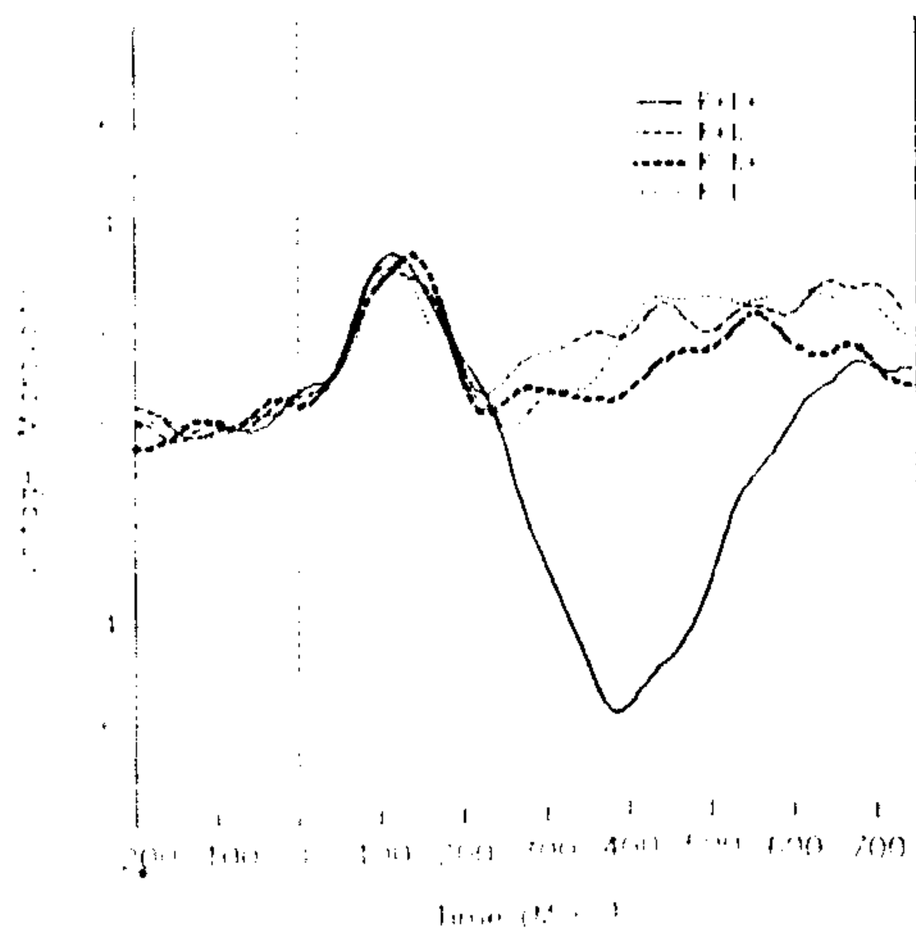

Figure A59: Sequential Position - Average ERPs at Pz for No Switch Middle

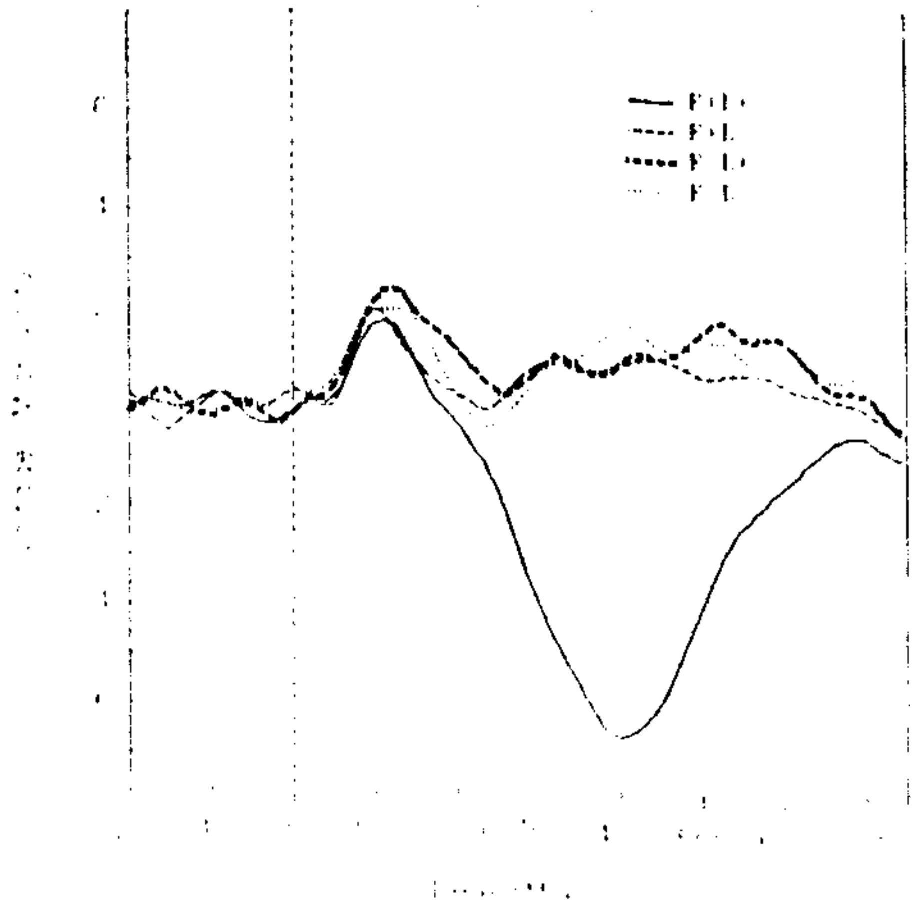

Figure A60: Sequential Position - Average ERPs at Pz for No Switch Late

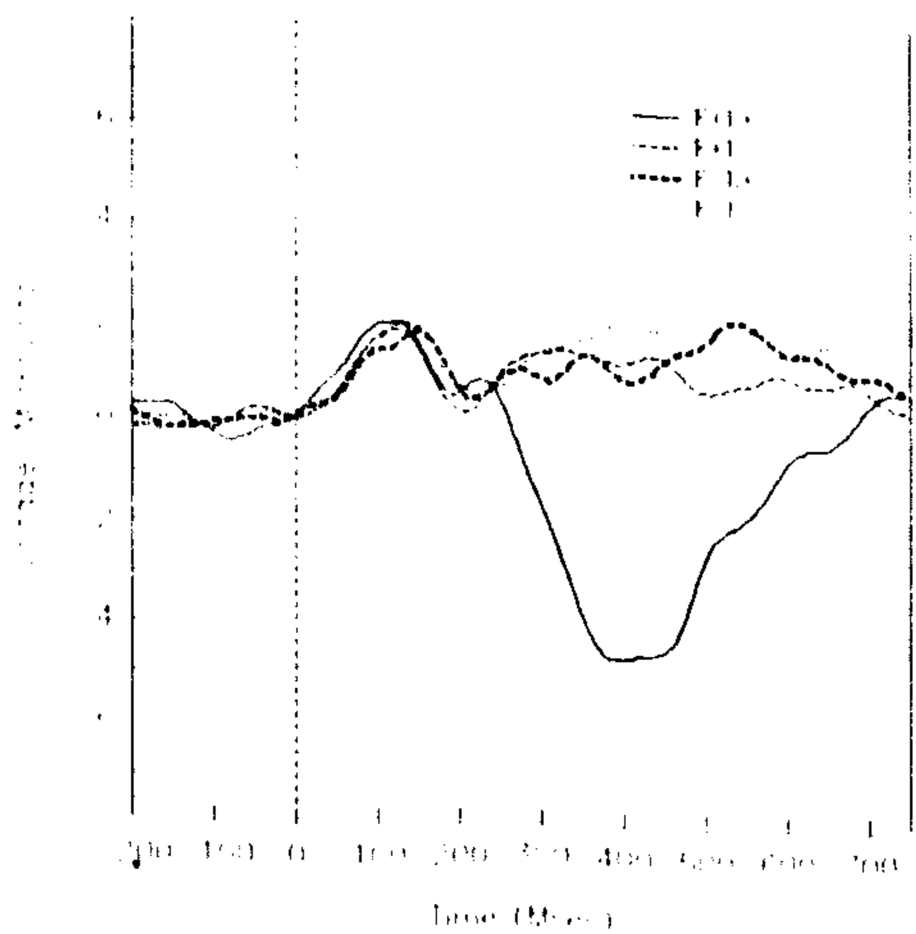

Figure A61: Sequential Position - Nd Area at Fz for Both Switch Early

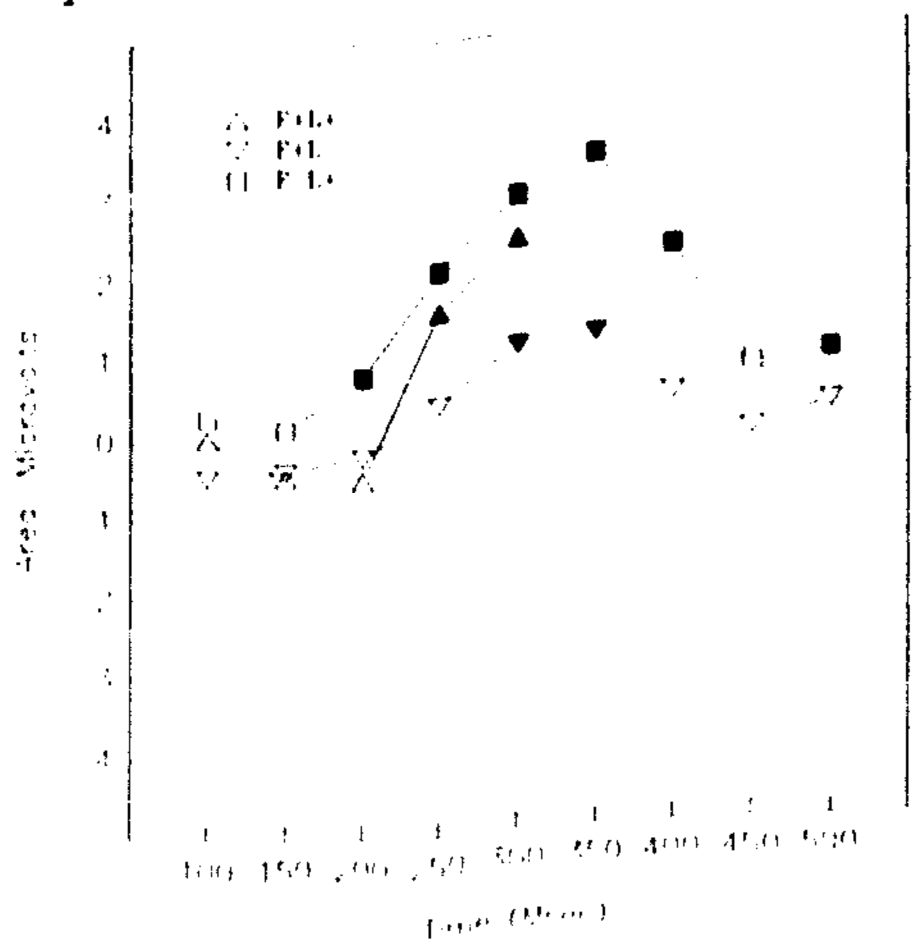

Figure A62: Sequential Position - Nd Area at Fz for Both Switch Middle

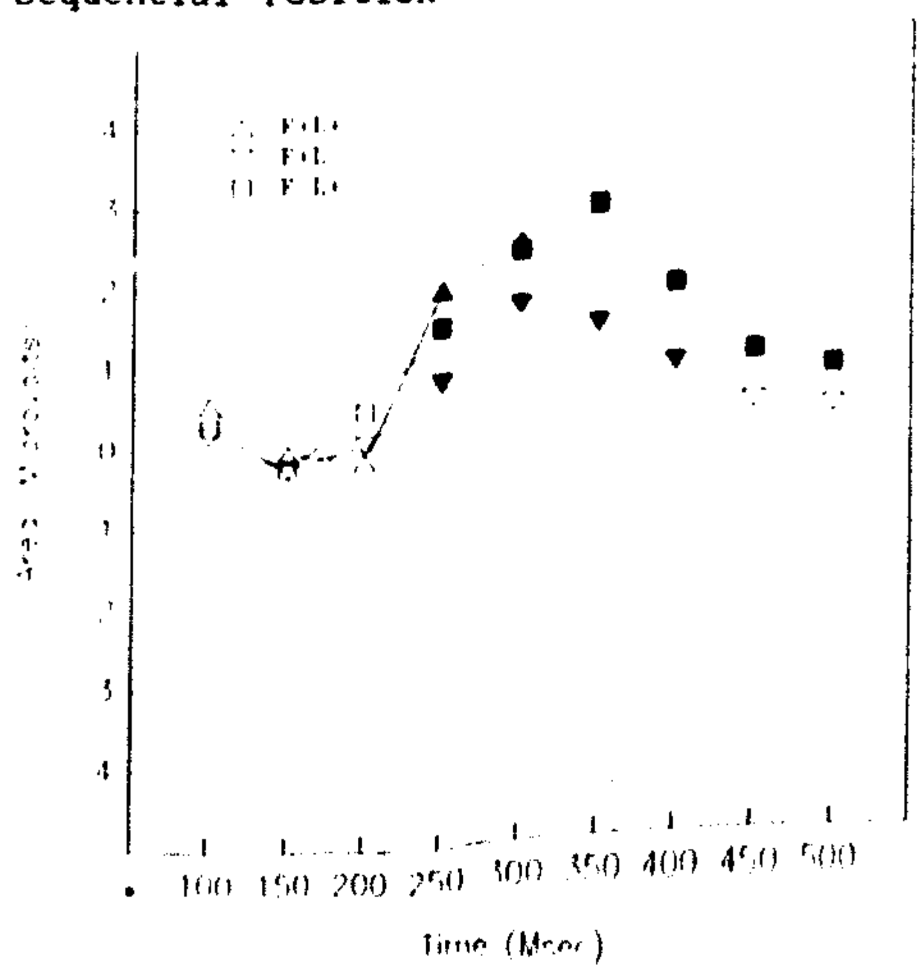

Figure A63: Sequential Position - Nd Area at Fz for Both Switch Late

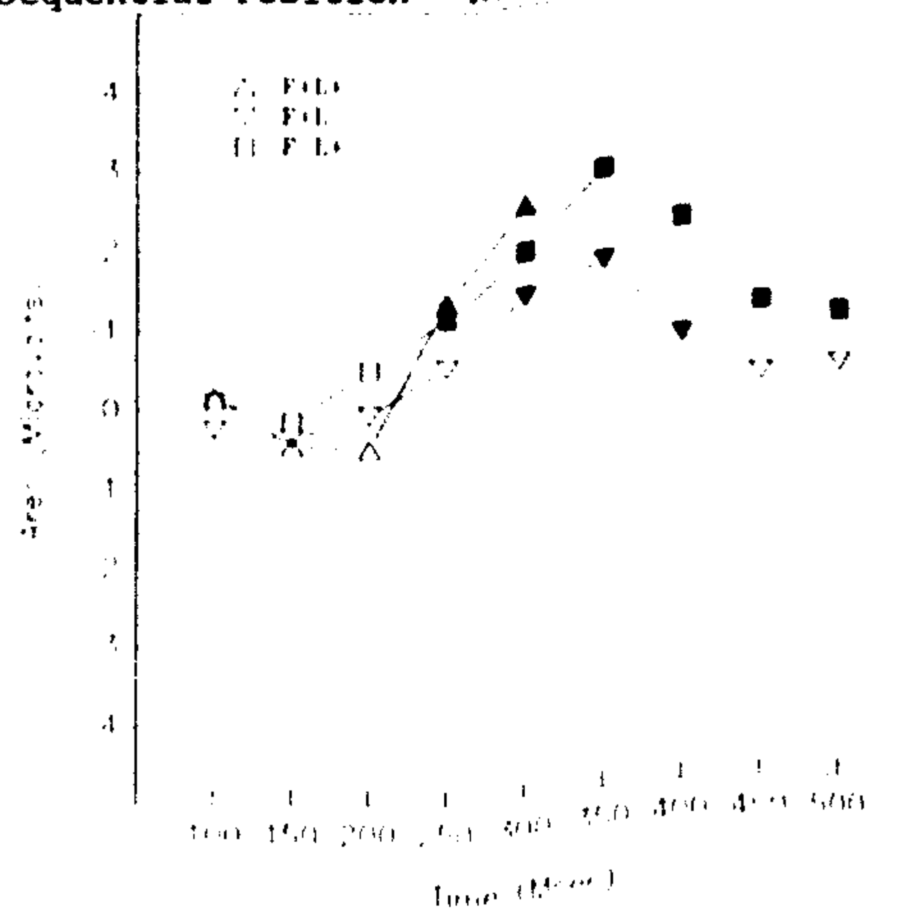

Figure A64: Sequential Position - Nd Area at Fz for Frequency Switch Early

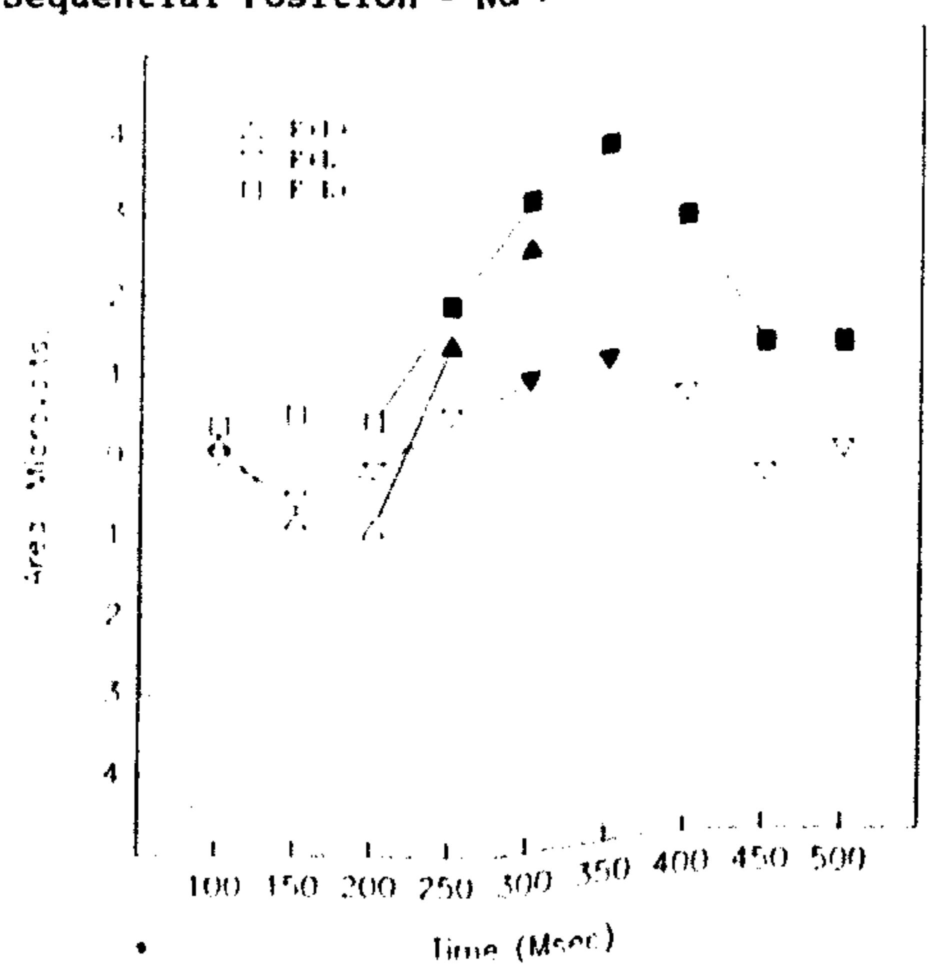

Figure A65: Sequential Position - Nd Area at Fz for Frequency Switch Middle

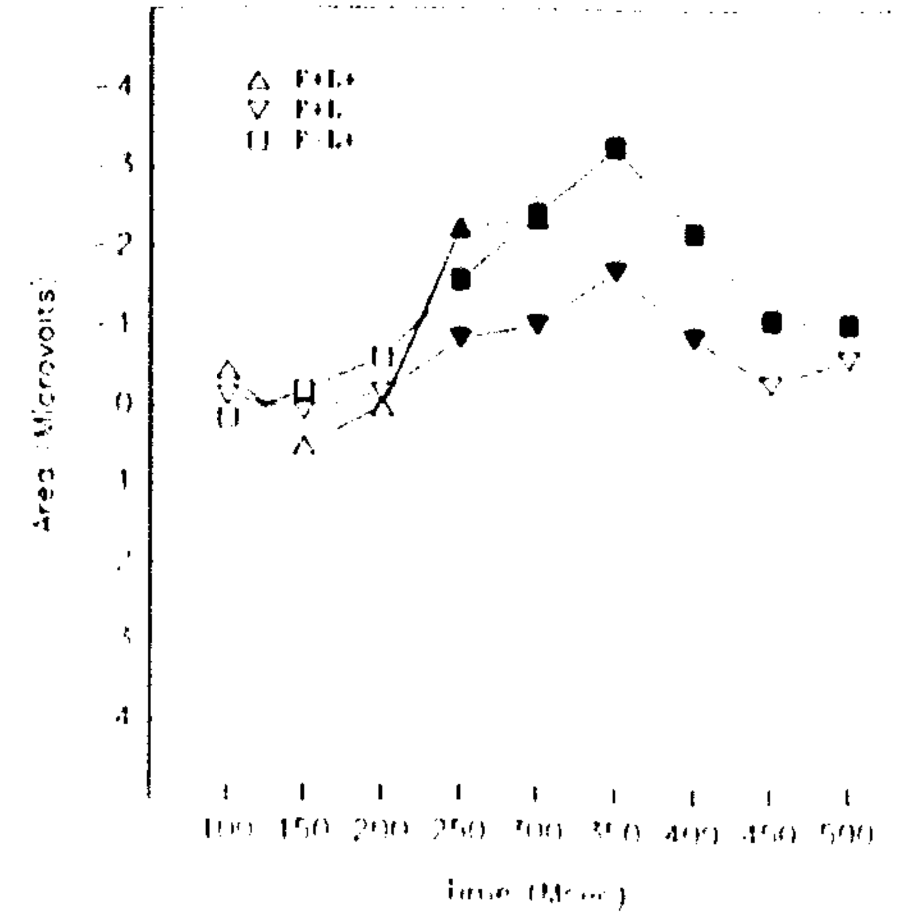

Figure A66: Sequential Position - Nd Area at Fz for Frequency Switch Late

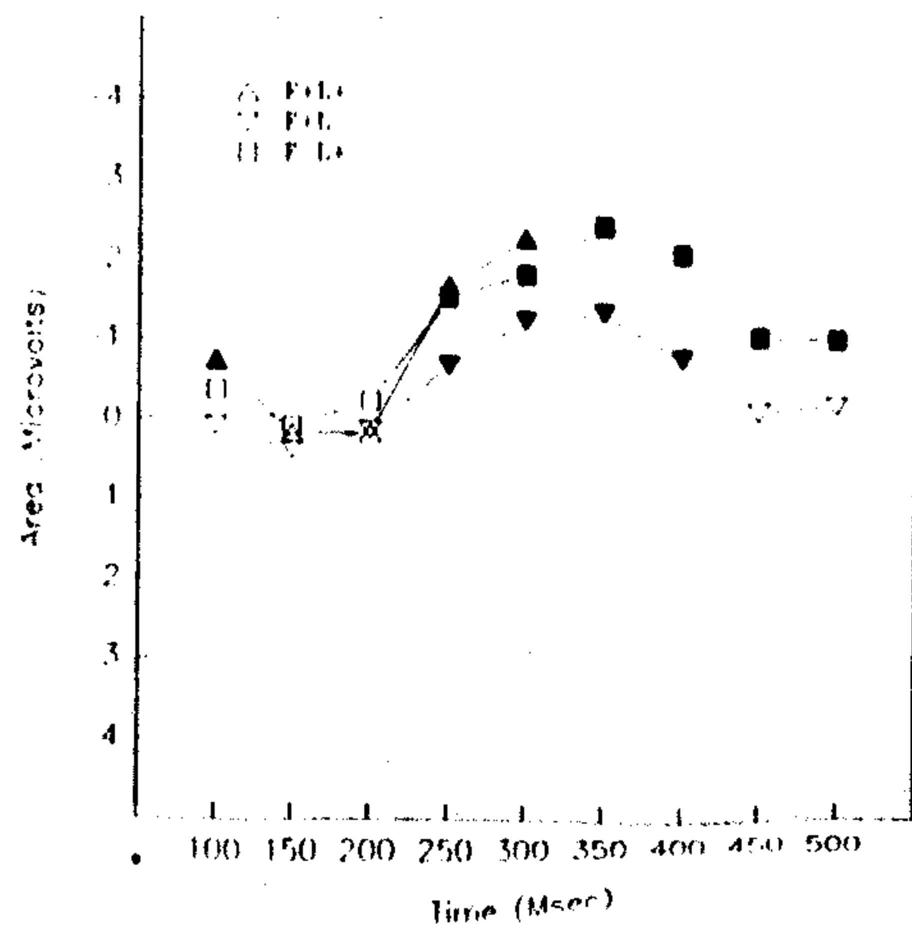

Figure A67: Sequential Position - Nd Area at Fz for Location Switch Early

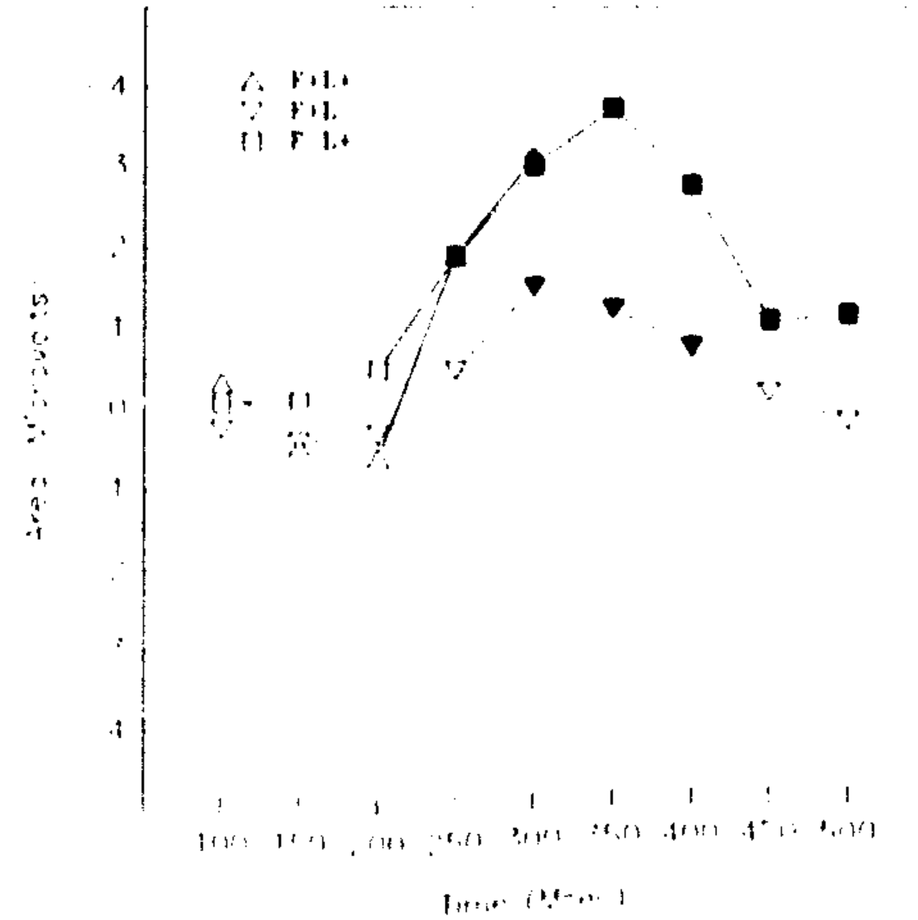

Figure A68: Sequential Position - Nd Area at Fz for Location Switch Middle

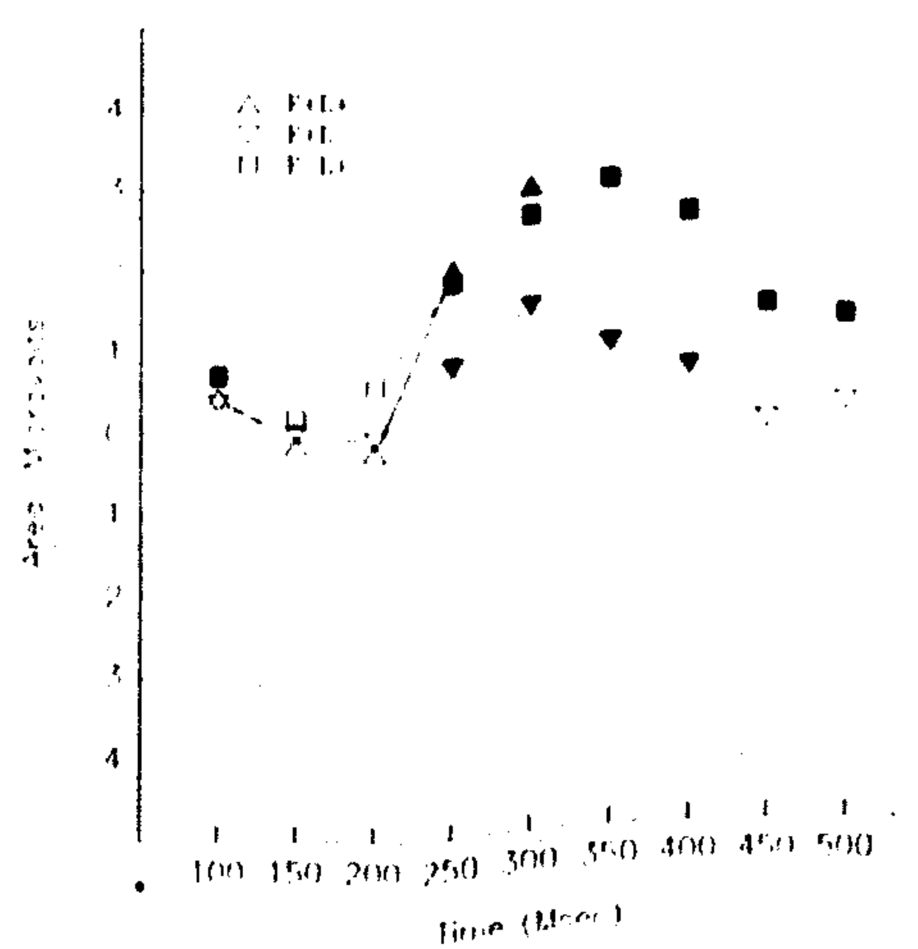

Figure A69: Sequential Position - Nd Area at Fz for Location Switch Late

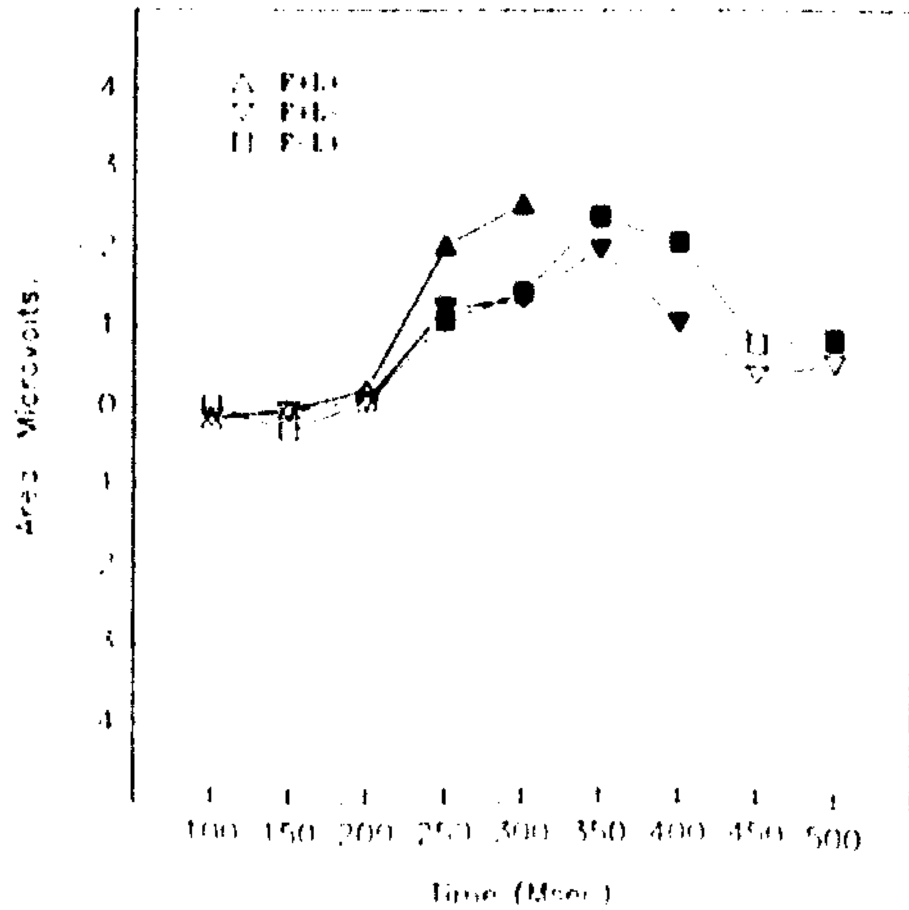

Figure A70: Sequential Position - Nd Area at Fz for No Switch Early

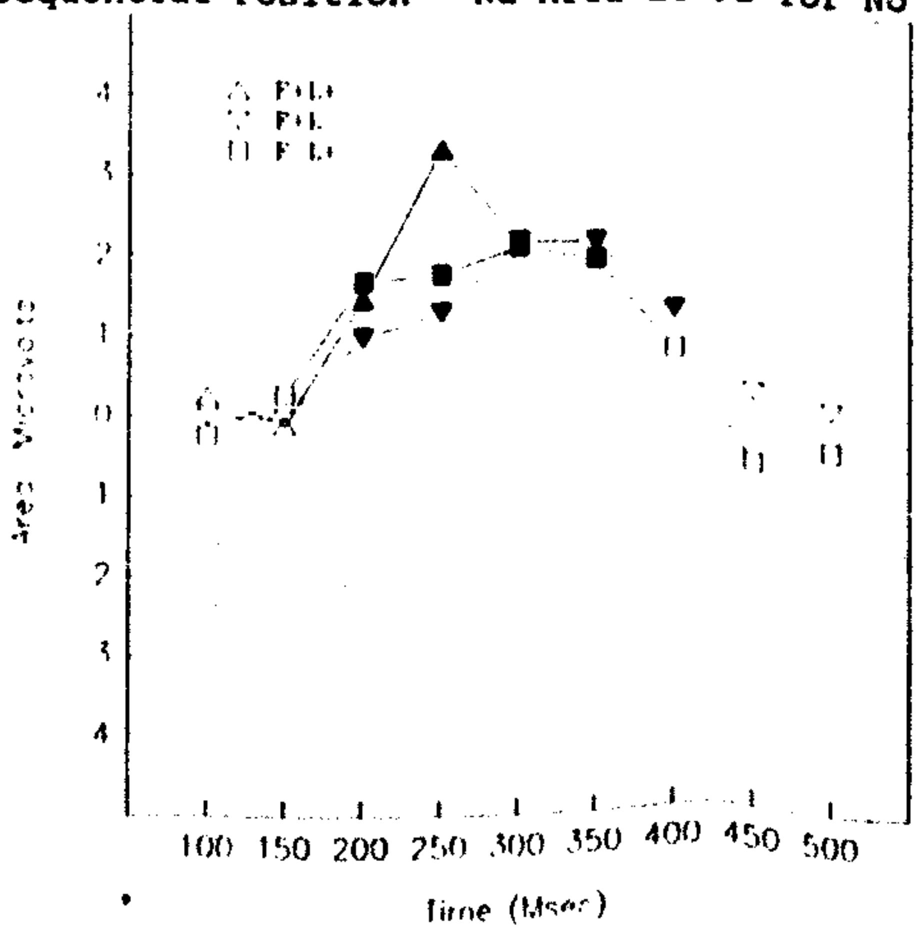

Figure A71: Sequential Position - Nd Area at Fz for No Switch Middle

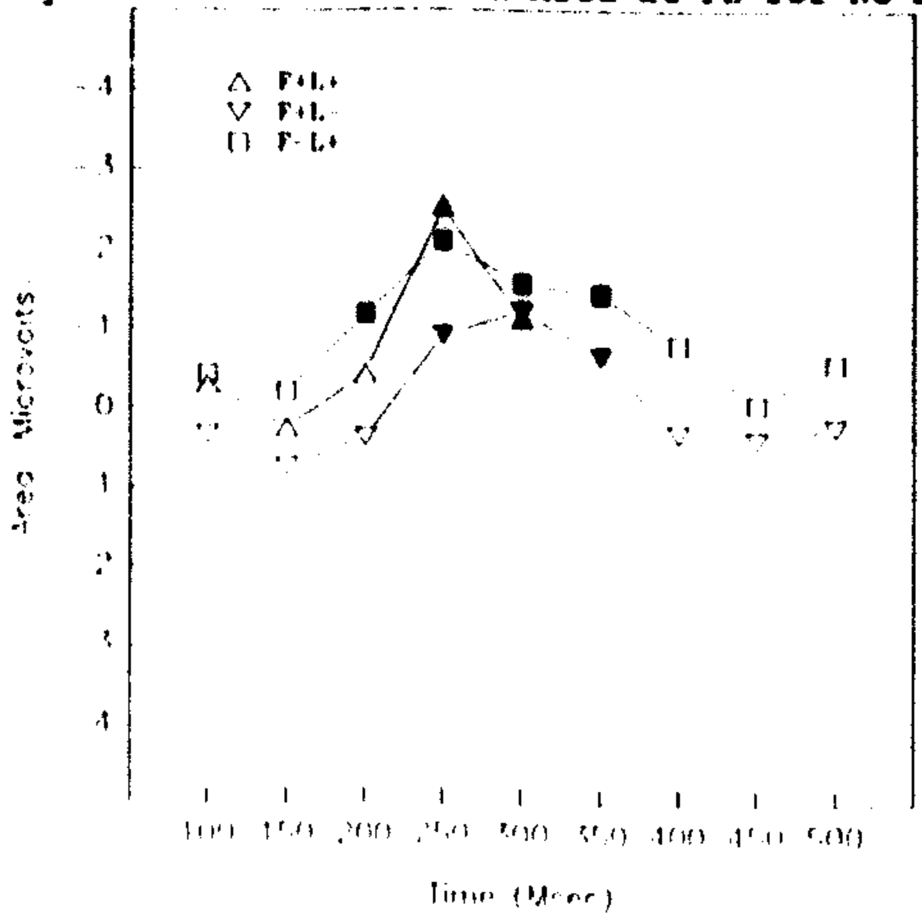

Figure A72: Sequential Position - Nd Area at Fz for No Switch Late

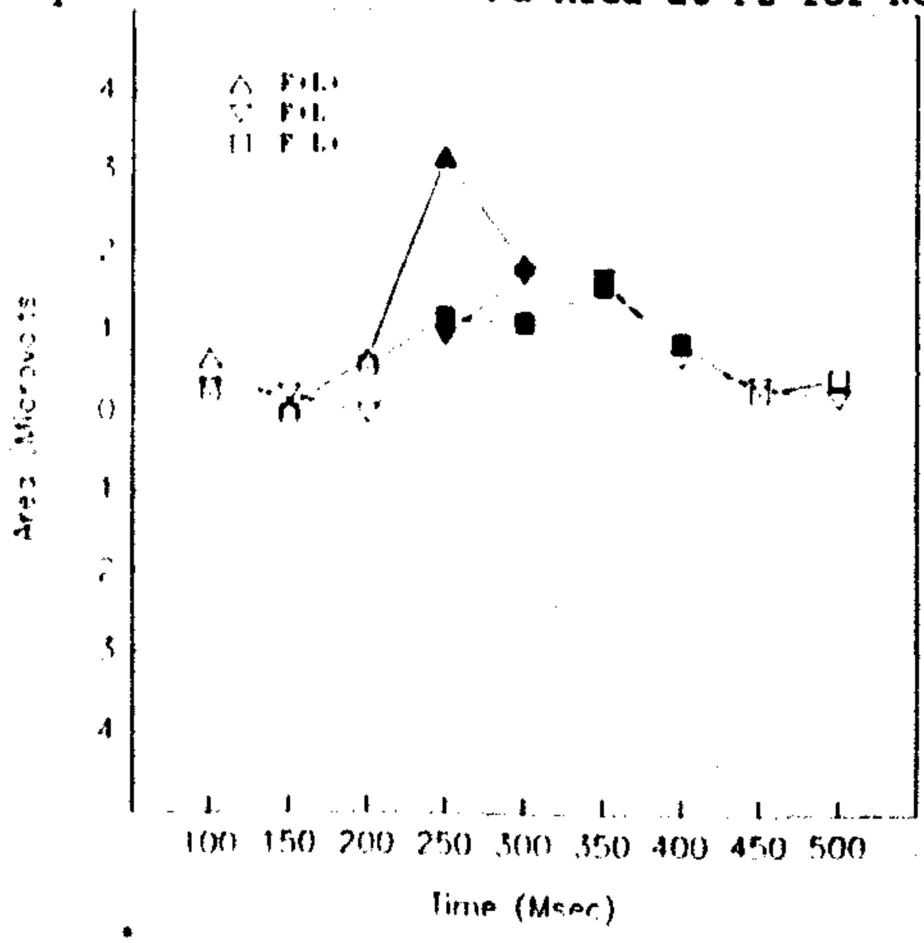

Figure A73: Sequential Position - Nd Area at Cz for Both Switch Early

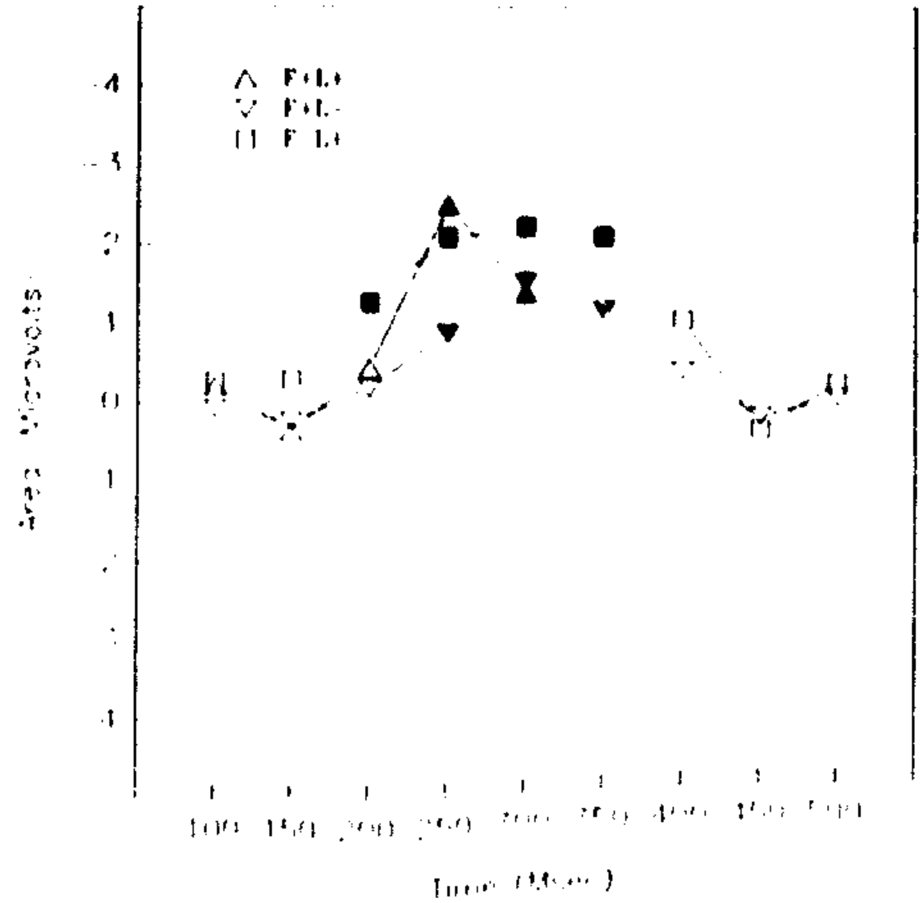

Figure A74: Sequential Position - Nd Area at Cz for Both Switch Middle

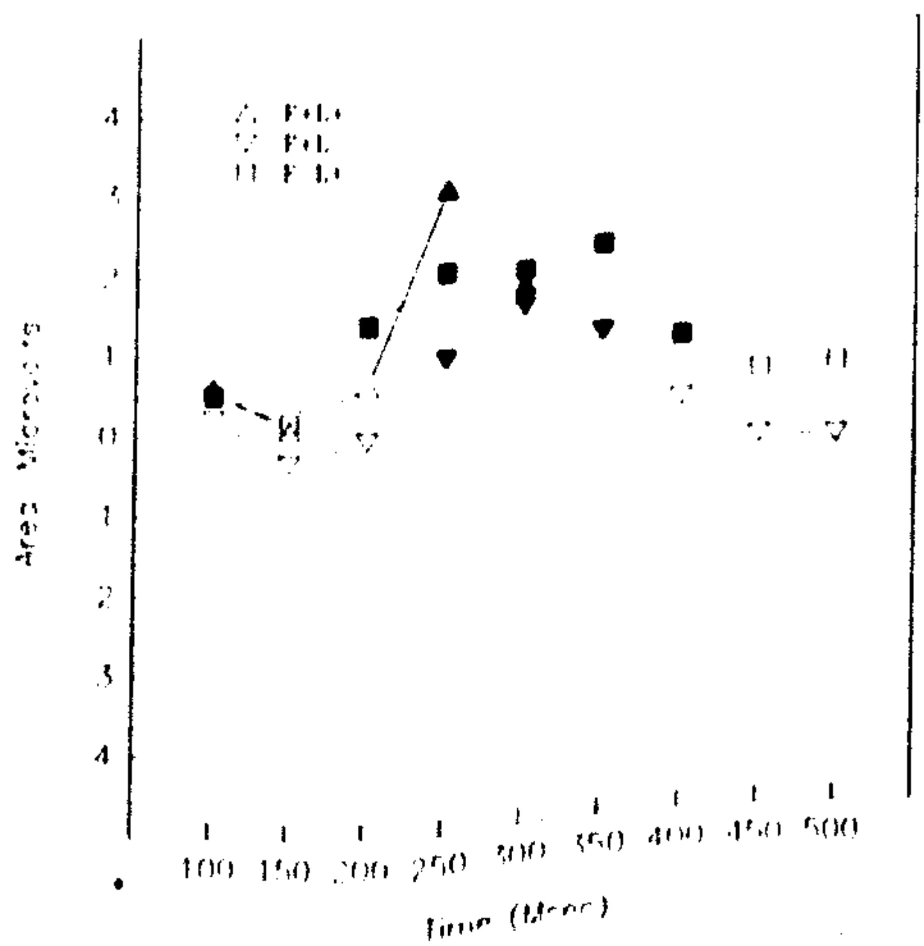

Figure A75: Sequential Position - Nd Area at Cz for Both Switch Late

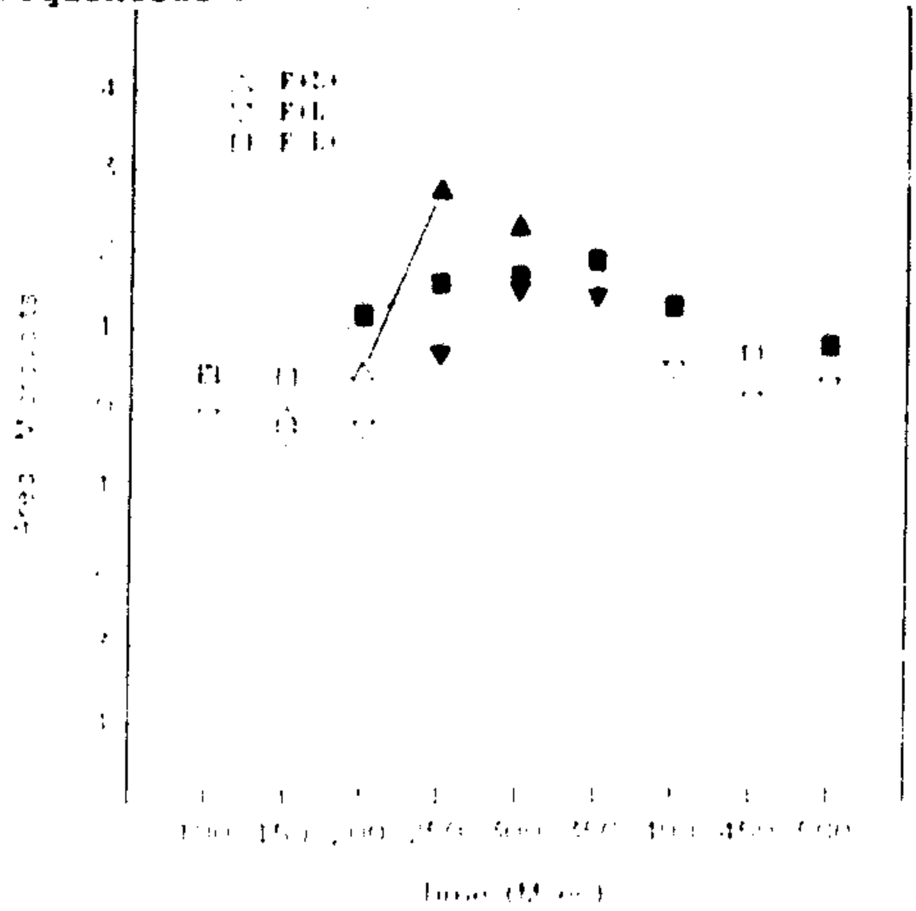

Figure A76: Sequential Position - Nd Area at Cz for Frequency Switch Early

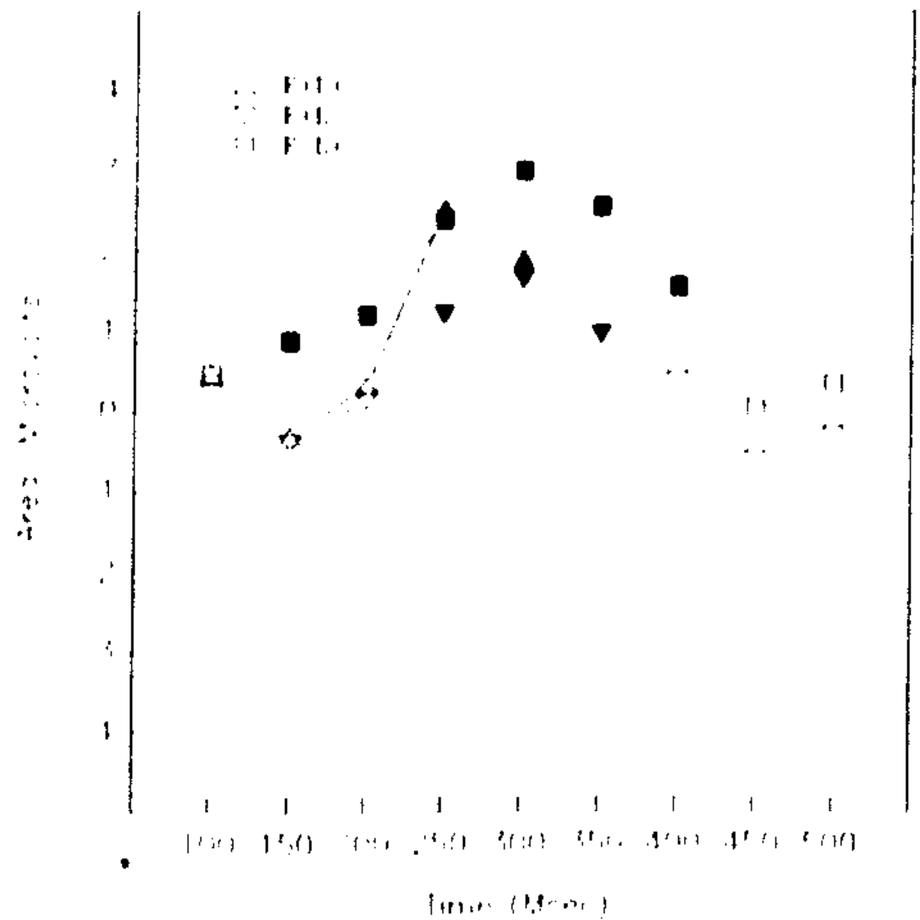

Figure A77: Sequential Position - Nd Area at Cz for Frequency Switch Middle

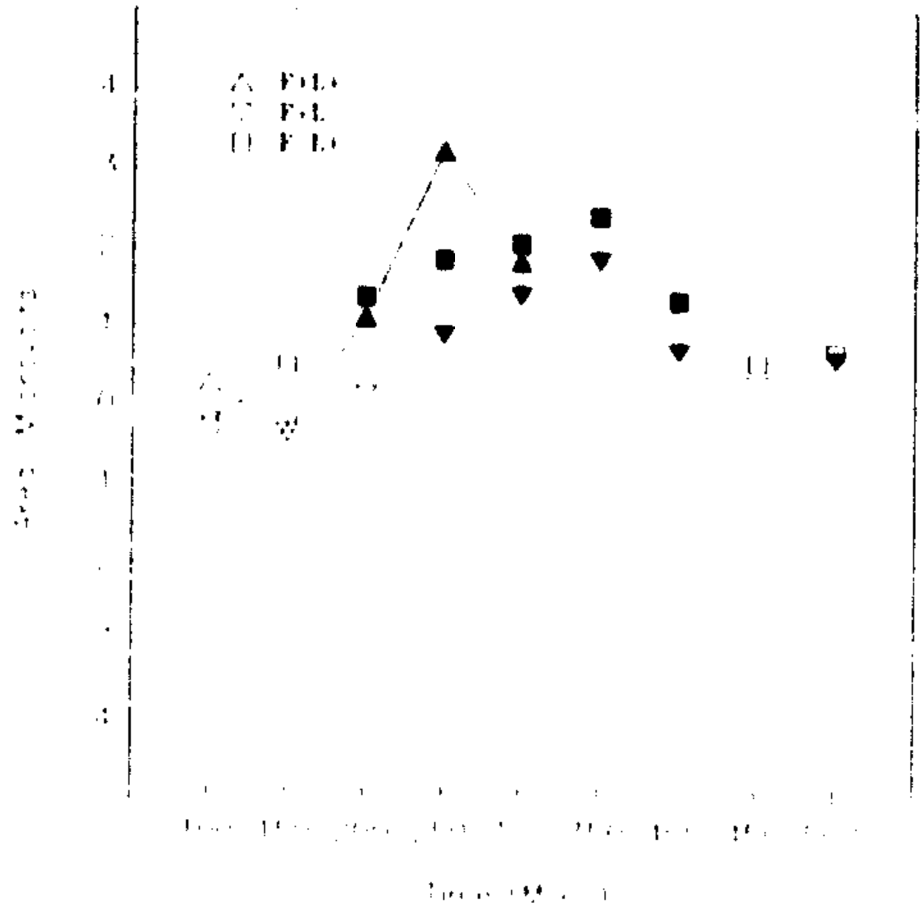

Figure A78: Sequential Position - Nd Area at Cz for Frequency Switch Late

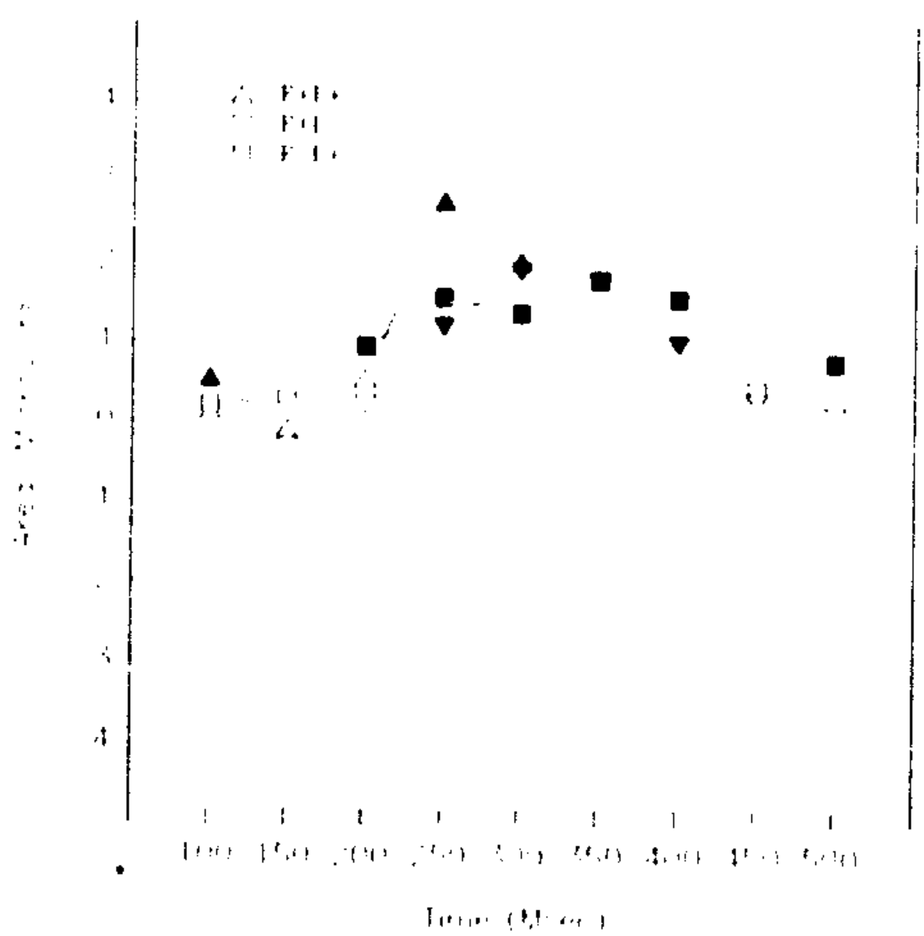

Figure A79: Sequential Position - Nd Area at Cz for Location Switch Early

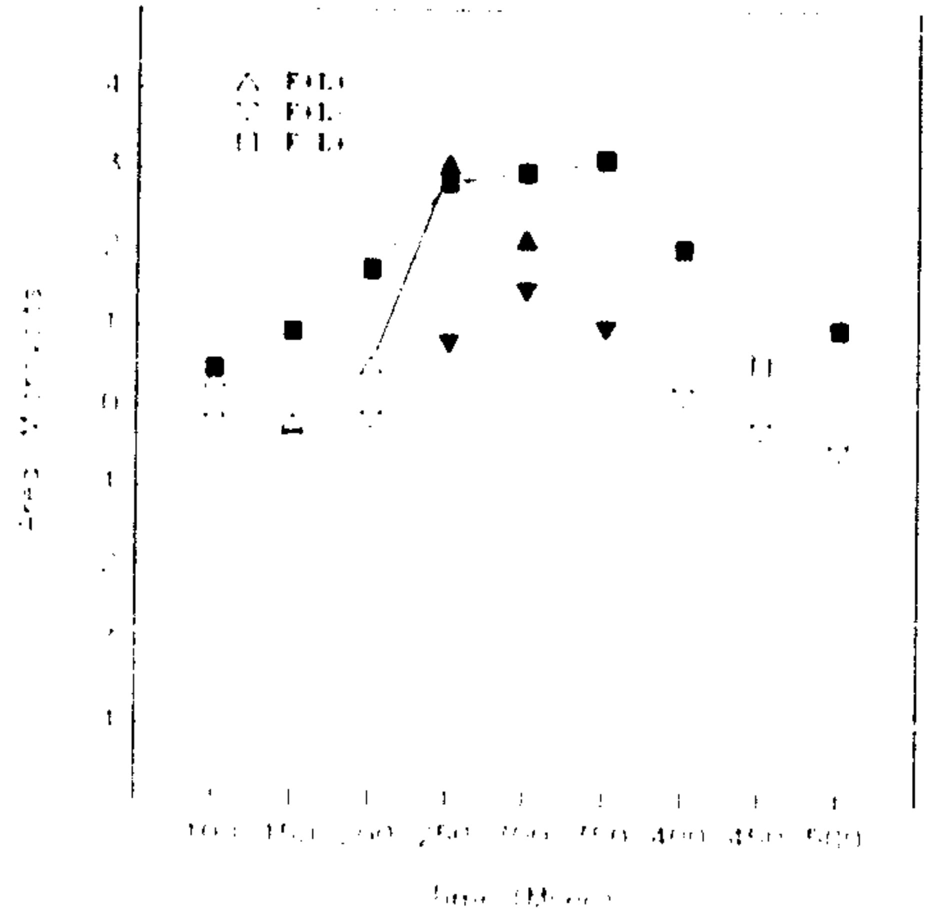

Figure A80: Sequential Position - Nd Area at Cz for Location Switch Middle

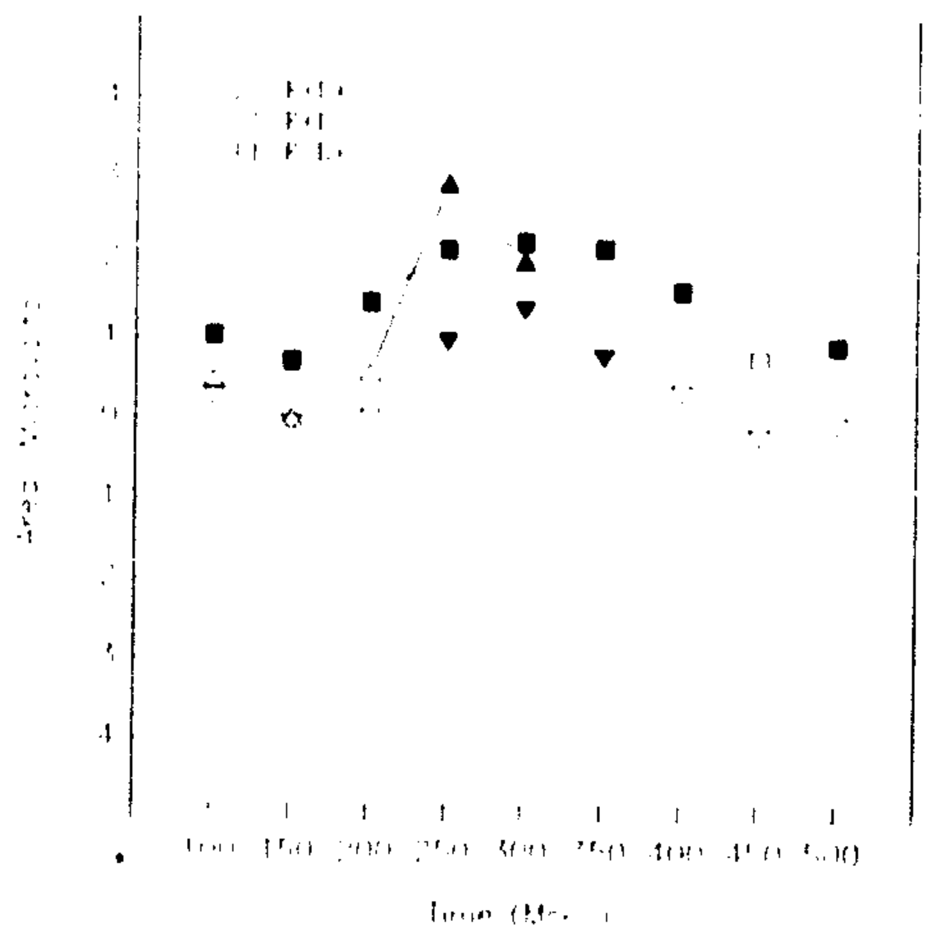

Figure A81: Sequential Position - Nd Area at Cz for Location Switch Late

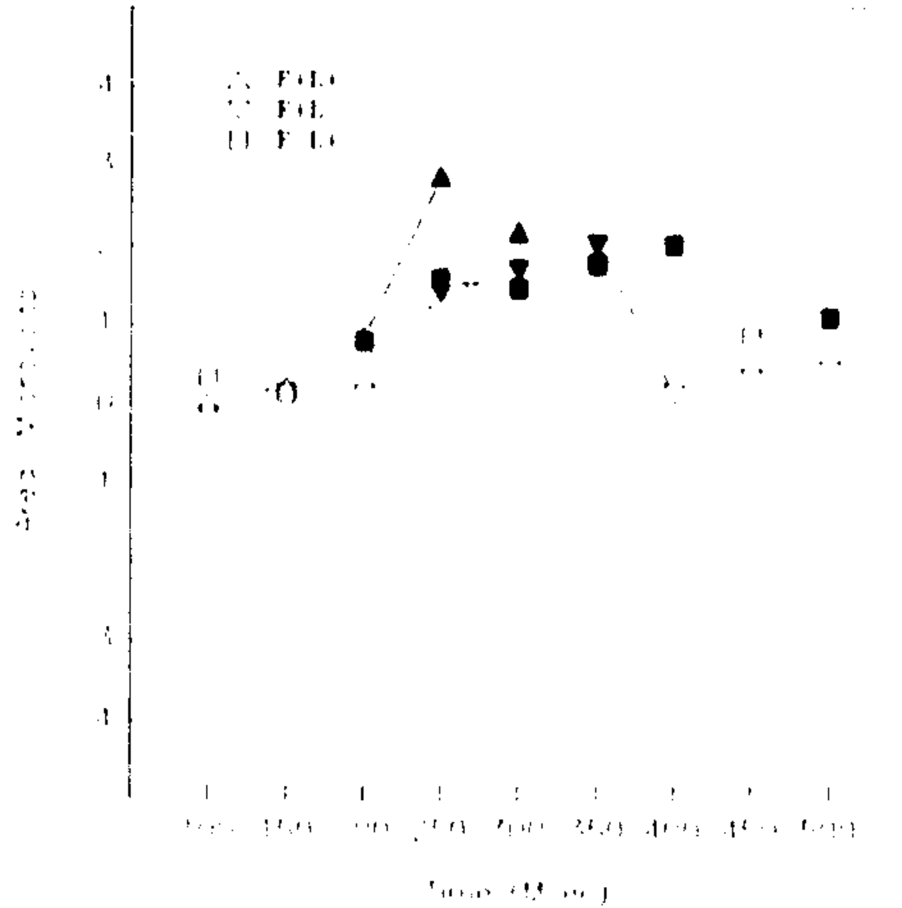

Figure A82: Sequential Position - Nd Area at Cz for No Switch Early

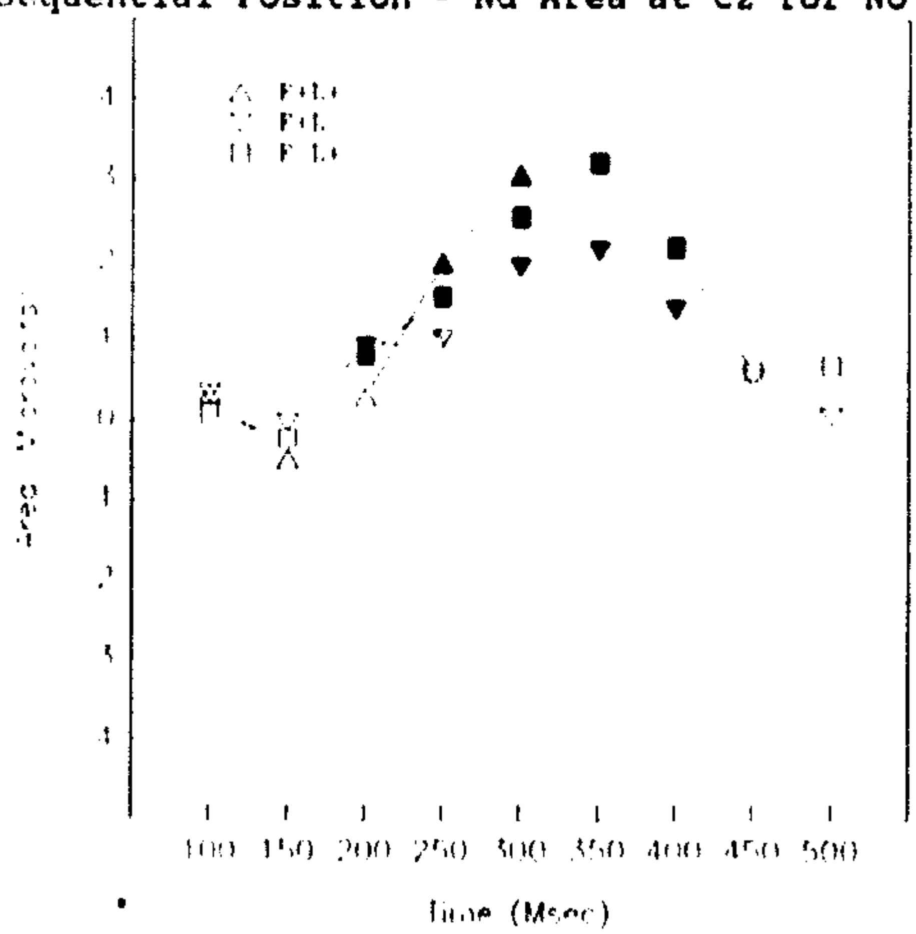

Figure A83: Sequential Position - Nd Area at Cz for No Switch Middle

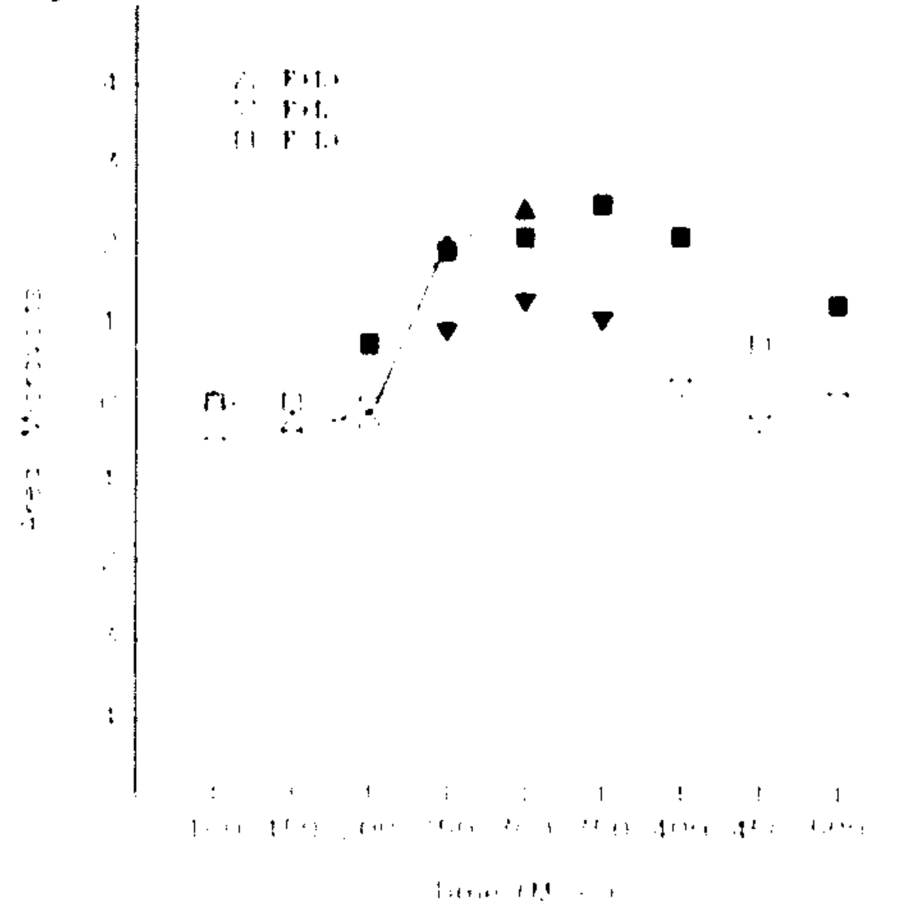

Figure A84: Sequential Position - Nd Area at Cz for No Switch Late