AUDITORY EVENT-RELATED POTENTIALS AS A MEASURE OF SENSORY SWITCHING TIME

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Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
DOCTOR OF PHILOSOPHY
December, 1993

OKLAHOMA STATE UNIVERSITY

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ACKNOWLEDGEMENTS

I wish to express my sincere appreciation to my major advisor, Dr. David G. Thomas for his supervision, guidance, encouragement and patience. I would also like to thank my other committee members, Dr. Bruce Ackerson, Dr. James Price and Dr. Robert Weber for their invaluable assistance in completing this manuscript.

I would like to extend my special gratitude to my husband Roger, and my daughter Devon for putting up with me during the difficult times, and for encouraging, supporting and loving me throughout this whole process. Enourmous gratitude and love also go to my parents for their major role in helping me achieve this goal. I would also like to express a special aknowledgement to my father for his insightful and practical assistance and advice throughout all phases of my research.

Finally, I would like to thank the Department of Psychology for providing me the facilities and environment necessary for conducting this research.

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Psychology is a science concerned with understanding normal brain and behavior functions. An understanding of these normal functions not only contributes to a broader scientific knowledge base, but can also lead to the identification and treatment of abnormal functions.

Auditory evoked responses are measurements of brain activity that have been shown to be very useful in the investigation of both normal and abnormal functioning of the brain. The following study was concerned with understanding a normal behavioral phenomenon known as the switching effect in terms of underlying net neural function. However, because electrical signals from the brain (evoked potentials) were used as the subjects' response to the stimuli, the present study was equally concerned with adequately processing these electrical signals in order to obtain the signal most representative of the neural function. Therefore, evoked potentials were measured in response to stimuli that were based on switching effect hypotheses, and these evoked potentials were put through both signal and statistical analyses.

The switching effect referred to in the above paragraphs has been manifested in two ways. The first occurs motorically as the increase in performance time that occurs when subjects are asked to alternate from one type of motor output to another rather than repeating a single motor output. It has been reliably demonstrated to occur when alternating among speech intensities and when alternating from whistling to humming.

The second type of switching effect occurs in the sensory realm. The switching effect in this case is not a result of alternating motor output, but occurs when sensory input is varied. Subjects have a longer reaction time when responding to varying stimuli than they do when responding to repeated stimuli.

Given that this behavioral phenomenon has been observed in both the motor and sensory realms, the present study investigated how the switching effect may be manifested in sensory neural activity. This was investigated using evoked potential measurements. Subjects were asked to listen to repeated and changed stimuli and the electrical responses of the brain evoked by these stimuli were measured. Because the evoking stimuli were of differing frequencies, sequence positions, and interstimulus intervals (ISI), the resulting signals could be compared and contrasted using measurements designed to examine their possible multiple component structure. These included latency measurements, frequency distributions, amplitude measurements and relative energy measurements as functions of the frequency, sequence position and interstimulus interval of the evoking stimuli. This allowed detailed examination of the structure of the signal and of the behavior of the signal based on the switching effect. The hypotheses based on the switching effect were that the responses evoked by changed stimuli would increase in latency and the responses evoked by repeated stimuli would either remain the same or decrease in latency. In the present study, there were no latency effects. However, the power spectral densities of the third response (T3) in the condition in which the third tone is the same frequency as the second, (SAME) varied with ISI differently from the way the power spectral densities of T3 in the condition in which the third tone was a different frequency than the second tone, (DIFF). This was a significant qualitative effect that occurred as a function of frequency changes in the evoking auditory stimuli. The significant quantitative effects in the investigation occurred as a function of sequence position and interstimulus interval.

Literature Review

Motor Switching

A large body of research on the control of voluntary movement has produced some convincing evidence of the existence of motor programs, i.e., "prestructured sets of central commands capable of carrying out movement essentially open loop" (Schmidt, 1988, p. 227), (James, 1890; Lashley, 1917; Henry & Rogers, 1960; Keele, 1968; Schmidt, 1976; Keele, 1973; Bizzi, 1979; Turvey, 1977). These early studies viewed the motor program as specific to a movement and fairly invariant, only modified slightly to correct errors by certain feedback from the sensory systems. The program is executed with a certain goal in mind and when the movements toward that goal are disturbed by the environment or by errors in program execution, feedback from sensory systems indicate these difficulties and in a few cases the program is modified to correct the difficulties. Although this model does explain voluntary movement, it has two major drawbacks: (1) The inability to explain storage and (2) the execution of novel movements (Schmidt, 1988). The storage problem entails the multitude of voluntary movements available to us. There are an estimated 100,000 programs required for speech alone (MacNerlage, 1970). This enormous number of programs would seem to be a crippling storage problem despite the large capacity of long term memory.

The novelty of movement problem is related to the storage problem. How do we make new movements? A basketball player makes many hook shots during his career and none of those shots are identical to any others, nor are they identical to the hook shots of any other player. How are all the subtle differences among the movements stored and activated?

A more viable model and one that overcomes the storage and novelty drawbacks is the generalized motor program. In this model, a program for a certain general class of movements is stored without full detail. Some aspects of the movement are invariant and some change from response to response with only the invariant features being stored as a program. The novel movements would involve changes in parameters of existing programs rather than changes and storage of many different whole programs.

Railbert (1977) demonstrated this in a publication using some examples of his handwriting in which the palindromic sentence "Able was I ere I saw Elba" was written in various ways: the right (dominant) hand, the right hand with the wrist immobilized, the left hand, the pen gripped in the teeth, the pen taped to the foot. The size, speed and stability of the writing among the different conditions were very different, but there were also obvious similarities in style among the conditions. Merton (1972) varied all the same aspects as Railbert in addition to varying between checkbook-sized and blackboard-sized writing. He also saw marked similarities in the writing. Schmidt (1976a) described the common features in the handwriting as the fundamental structure of the motor program and the varying features as the changeable parameters of the motor program.

Additional support for this model comes from Quinn and Sherwood (1983). Subjects made elbow flexing or extension movements past a switch. The movement from beginning to activation of the switch took about 400 ms except when an auditory signal was given to either speed up the movement in progress or reverse the movement in progress. It was found that the time to make the change was 100 ms faster when an increase in movement speed was required than when a reversal in movement was required. The reversal was explained as a change in program while the increase in speed in the movement was only a change in a parameter of a program and therefore took less time to initialize. Roth (1988) found that the length of time to change a tennis ground stroke to a lob was 609 ms, while the time to change the angle or length of a ground stroke was 403 ms and 413 ms, respectively. Presumably, the change in stroke was a change in program, while the changes in direction and length were only changes in parameters and therefore took less time to initialize than a whole program change. Regardless of the type of change, program or parameter, a definite switching time effect was observed; changes in program or parameter took more time than no change in program or parameter.

Weber and his colleagues have demonstrated another type of switching time effect in a series of studies using various motor responses. The first study of interest was done by Weber, Blagowsky and Mankin in 1982. The main experimental question asked was, does a switching time effect exist for the generative speech mode when alternating among different intensities of speech? The peripheral questions predicated on the existence of a switching time effect are: 1) Is the switching time effect due to moving from one category in memory to another? If this were the case, one would expect the changing of intensities or response characteristics to become faster with practice. This is the case when stimulus characteristics are changed, i.e. changing from letters to digits. 2) Is the switching time effect peripheral rather than central, i.e. is it time needed to change loading and movements of the peripheral motor system (going from lesser to greater constrictions of the larynx to dampen sound from yelling to whispering). 3) Is the effect an analog or a digital one? That is, is there a central switching mechanism that merely exchanges one value (in this case intensity) for another and takes the same amount of time to make this change regardless of the magnitude of the change, or is there an analog pointer system which moves along a continuum of values taking more time to go from one end of the continuum to another than to go from the middle of the continuum to an end?

These questions were addressed by Weber et al. in a series of four experiments. The four experiments found that alternating among speech intensities does take longer than producing any one intensity alone. In other words, an intensity switching effect did occur and was not significantly altered even when subjects were given practice with the task. The investigation also found that switching effects were very similar for all conditions. It took subjects no longer to go from mouthing (speaking with no voice) to yelling (speaking with great intensity) than it did to go from mouthing to speaking (normal speaking intensity). The investigators concluded that the switching time effect is not a function of memory overload, nor is it a manifestation of a lack of familiarity with the task which can be overridden by practice. The switching time effect also does not appear to be a peripheral effect due to muscle stretching and dampening. This conclusion comes from the data indicating that the switching time effect is identical among different intensities along a continuum. If the effect were peripheral, one would expect a greater distance between intensities to result in a larger muscle movement which would take a longer time to complete. These data also support a digital switching process rather than an analog switching process. If the switching occurred in analog, a pointer moving along a continuum of intensity values, one would expect intensities further apart on the continuum to take longer to switch between than intensities closer together on the continuum (i.e. going from mouthing to yelling would take longer than going from mouthing to speaking). On the other hand, if a central switching mechanism were responsible for the changing intensity parameter, all changes would take the same amount of time. It would not matter how far apart on the continuum the intensities were.

Weber et al. concluded in the series of four experiments that a centrally-controlled robust switching time effect occurs in the generative mode. It would seem that there exists an intensity function into which different intensity parameters can be placed.

Weber, Holmes, Gowdy, and Brown (1987) also found a switching time effect to be present in motor programs with musical output. When subjects were asked to alternate between singing and whistling, the output time was again much longer than when only singing or only whistling was required.

Weber, Burt and Noll (1986) investigated switching time between attention and perception. Subjects were asked to produce letters from memory in the memory-only condition, to read letters from a display screen in the perception-only condition and alternately produce a letter from memory and read a letter from a display screen in the switching condition. The experimental question asked was: Will any of the three conditions result in a significantly different production time? It was found that although the memory-only and perception-only conditions did not differ significantly from each other, the switching condition required longer production time than either the memory or perception-only conditions. This effect did not decrease over trials and did not therefore seem to be affected by practice.

The preceding studies have dealt with the effects of changes in motor programs on motor output. It appears that changes in the parameters of a previously executed motor program take time to implement and that this extra time is manifested in an increase in the execution of the motor response.

In Weber et al., (1986), the switching effect was demonstrated to occur with a change in stimulus parameters rather than a change in response parameters. It appears that the switching effect is a phenomenon which can be induced by changes in input or output. Changes take time to implement regardless of their source. The first execution of a movement or the first presentation of a stimulus appear to set up existing sets of stimulus and/or response parameters which must be removed and replaced when movements or stimuli are changed. The internal representation of a novel stimulus or response appears to be very different from the internal representation of a repeated stimulus or response. The novel has no active representation and one must therefore be set up. The repetition is launched from an already existing set of parameters. If a change is slight, the existing representation is merely altered slightly in its parameters, resulting in a switching time effect.

The switching effect has been adequately demonstrated in the motor realm by the above reviewed studies. Implicitly, when an increase in response time occurs because of a change in program or parameters, no change or a decrease in response time may be expected when a program parameter remains. This premise is investigated in the following studies in which stimuli and/or response are repeated and it is determined whether a savings in reaction time occurs.

Repetition Effect

The repetition effect is a savings in reaction time from the first to the second of two consecutive stimuli and/or responses. It was first reported by Hyman (1953) in a study designed to determine how the amount of information present in a stimulus affected the reaction time to that stimulus. Subjects vocally responded to the onset of a light in a 6 x 6 light matrix. It was found that when a stimulus was repeated, the reaction time to the second presentation was unusually fast. This effect occurred regardless of the subject's voiced expectancy of the stimulus.

In a more thorough investigation, Bertelson (1961) presented subjects with three conditions. Subjects responded with a key press under a light on the right or a light on the left. In one condition, the lights were lit randomly (RAND). In another, there was a series of repetitions of the light sequences (REP). In the third condition, the lights were alternately lit (ALT). It was found that subjects responded much faster in the REP condition than in either the RAND or ALT conditions. Bertelson concluded that subject must prepare for each response and that for some reason, with short time lags, (50 ms), the preparation time is much less for repeated than for non-repeated events and that this advantage exists even without practice. With longer time lags (500 ms), some subjects did better with repetitions and some with alternations. In a study designed to test the effect of the time lag, Bertelson and Renkin (1966) found that increasing the time lag from 50 to 200 to 500 to 1000 ms led to a decrease in the difference reaction times to repeated vs. new stimuli, but a small repetition effect was still evident. Hale (1967) also found a decrease in the repetition effect as a function of increasing time lag. These findings suggest that the repetition effect is somewhat "automatic" in nature and that given longer preparation periods, subjects consciously prepare different strategies for dealing with incoming stimuli.

The repetition effect occurs in difficult as well as simple tasks. When Bertelson (1963) asked subjects to give incompatible stimulus response relationships (i.e. press the left key when the right light flashed), their reaction times were facilitated to repeated stimuli. Similarly, Felfoldy (1974) found the repetition effect present when the stimuli were more complex than light flashes. Subjects were asked to classify rectangles which varied in height and/or width by pressing one of two buttons. Reaction time to repeated stimuli (rectangles of the same height and width) was shorter than reaction time to one changed dimension and two changed dimensions, respectively.

The above studies on the repetition effect suggest that the decrease in preparation time described by Bertelson may be due to stimulus parameters being formed after one presentation of the stimulus. Those stimulus parameters then facilitate the next response to that particular stimulus. If the parameters are already stored, the time needed to perform the storage function is saved resulting in an overall savings in reaction time to a repeated stimulus.

Once the repetition effect was consistently observed, the next question asked was, is the repetition effect a result of a repeated response, a repeated stimulus or both? If it was found to be a response effect, it might be viewed as a motor switching effect: a savings in reaction time due to a repeated motor program rather than an increase in reaction time due to a changed motor program. If, however, the repetition effect were the result of repeated stimuli, the effect could be viewed as one of sensory processing. A stimulus would establish a representation of a set of parameters that subsequently leads to a savings in the processing of a repetition of that stimulus.

This question has been investigated using a paradigm in which the same response was given for different stimuli. Two colored light flashes are assigned to one key press and two other colored light flashes to another key press. In this way, repeated responses could be compared to stimulus-response repetitions to determine whether response repetitions alone were sufficient to account for the repetition effect. Stimulus-only repetition effects were inferred by subtracting the response repetition effect from the stimulus-response repetitions. There are some conflicting results associated with this paradigm. Bertelson (1965) and Rabbitt (1968) found that response repetitions were sufficient to account for the savings in reaction time found, while Smith (1968) found that stimulus repetition accounts for the savings in reaction time measured.

Because of these conflicts and because the above-described paradigm does not allow for direct assessment of the stimulus-only repetition contribution to the repetition effect, Ells and Gotts (1977) designed a study to further investigate the relative contributions of stimulus and response to the repetition effect. A digit which was to be classified as belonging to a target set consisting of two different digits was presented on one of two separate screens. The subject would not respond if the digit were not a target stimulus. If the digit were a target stimulus, the subject would respond by pressing a key under the display screen on which the digit appeared. This paradigm allowed a comparison of response repetition, without stimulus repetition, stimulus and response repetition, and stimulus repetition without response repetition. In a series of three experiments, Ells and Gotts found that response repetitions contributed little or negatively to the repetition effect, stimulus repetitions led to large repetition effects and that stimulus-response repetitions also led to large repetition effects due, it was assumed, to the stimulus repetition involved since response repetitions alone had shown little effect.

Kerr, Davidson, Nelson, and Haley (1982) in a similar paradigm, also found that stimulus repetition led to the largest repetition effect. Kerr et al. (1982) compared the repetition effect found in adults to that in children and reported that stimulus repetitions accounted for the repetition effect in both adults and children.

These early works establish the existence of a basic repetition effect to fairly simple stimuli (light flashes, digits, letters). It seems that, at least with simple stimuli, the repetition effect is a result of stimulus repetition, not response repetition. This implies a sensory processing explanation for the effect: The repetition in stimulus leads to a savings in processing that stimulus. Other investigations into the effect of stimulus repetition have employed far more complex stimuli and reach more complicated conclusions associating the repetition effect with different types of memory.

Some of these more complex studies, while not directly related to the proposed problem, do provide some applications of the more basic principles postulated by the simple repetition effect studies.

Miller and Anbar (1981) tested the effects of expectancy and stimulus frequency on character identification. Stimuli were presented with high and low visual quality and high and low stimulus-response compatibility under high and low expectancy and high and low stimulus frequency. Stimulus frequency involved different probabilities of stimulus presentation. It is somewhat different than stimulus repetition in that, although a stimulus may appear several times during a session, it may or may not appear two or more times in succession and therefore becomes more a product of longer term memory than a product of savings due to an existing representation of stimulus parameters. Stimulus frequency in Miller et al. had a more significant interaction with visual quality than did expectancy. However, expectancy was more important than repetition in the low stimulus-response compatibility condition.

Ashcraft and Battaglia (1978) presented simple addition problems for true-false verification and found that reaction time to unreasonable wrong problems was faster than to reasonable wrong problems; correct problems had the fastest reaction time of all. A second experiment replicated the earlier results and found that repetition facilitated all reaction times.

Faust-Adams and Nagel (1975) presented non drivers with control panels from European and American cars. Subjects were asked to reach for different parts of the control panels. When stimuli were repeated, there was a facilitation in reaction time. Holding and Holding (1989) presented subjects slides of intersecting suburban routes. Subjects saw each slide either one or three times and then were asked to draw a map of the route they had seen. Repetition of the stimuli had no effect on the subjects' ability to perform the task.

It seems that in more complex tasks, the repetition effect is not as pronounced as in simple tasks. Perhaps this and Bertelson and Renkin's (1966) findings on time lags indicate that the repetition effect is a very basic "automatic" occurrence that is overridden when more complex cognition is needed for a task or when longer time lags allow a conscious take-over of the automatic process that leads to a repetition effect.

Sensory Switching Time

It has been demonstrated in the above studies that a change of a response results in an increase in response time. This has been explained as time needed to change the response parameters of a motor program.

It has also been demonstrated that a repeated stimulus leads to a savings in response time and a changed stimulus leads to an increase in response time. The proposed study is an attempt to reveal a neural mechanism responsible for the demonstrated behavioral repetition and switching effects. The primary questions posed are: Does one presentation of a stimulus somehow prime the sensory neurons involved to react faster to a repetition of that stimulus? Conversely, does a change in stimulus require a change in the neurons involved in the response to that stimulus resulting in a longer response time? Before these particular questions can be evaluated, a short synopsis of the structure and function of the auditory cortex is needed. Before neural repetition and switching effects can be evaluated, the neurons involved in auditory responses must be described. Are there specific neural populations that respond to specific parameters of sound, i.e., frequency and location? If so, do the specific neural populations respond as a whole to stimulation by that particular sound parameter, or are there organizations within the neural populations that respond to variations in parameters? If there are frequency-specific neurons and location-specific neurons, then perhaps the repetition and switching effects can be observed at the level of the sensory neuron through repetitions and changes of frequency and location parameters of an auditory stimulus.

Animal Lesion Studies

Because of the structural similarity of their auditory cortices to the human auditory cortex, cats and monkeys are the main subjects in animal studies of the auditory cortex.

The methodology of the animal studies investigating sound localization and frequency response usually involves training an animal to respond in a certain way (i.e., eating at a specific location from which a sound is emitted, orienting the body toward the location from which a sound is emitted, avoiding shock which is signaled by a certain frequency tone, etc.). Once the animal is responding in a consistent way, surgical ablations are made in the auditory cortex. These ablations may be either unilateral (in one hemisphere) or bilateral (in both hemispheres). The animal is then again made to perform the sound localization or frequency discrimination task and its post-surgery performance is compared to its pre-surgery performance. Any change in performance is attributed to an interruption in function due to the location of the surgical lesion. The location of the lesion is then inferred as the location of the function that has been lost or interrupted.

The animal studies of lesioned areas of the auditory cortex indicate that selective neurons operate together to localize sound in contralateral space. These indications come from the results of the following studies which show that when the auditory cortex is lesioned either unilaterally or bilaterally, the animal's sound localization function is interrupted. The interruption in function occurs even when the animal's ears are left intact and other auditory functions remain (i.e., the animal can still hear sounds; it is merely unable to determine the direction from which the sound occur). Diamond and Neff (1957) and Neff (1977) have reported that bilateral ablations of the auditory cortex of the cat affect the discrimination of change in temporal patterns of sounds. Heffner and Masterson (1975) report that after a bilateral ablation, a monkey is unable to approach a sound source correctly. Strorminger (1969) found deficiencies in localizing performance of cats after some unilateral lesions of the auditory cortex. When the ear contralateral to the unilateral lesions is stimulated, the loss of localization is much greater than when the ipsilateral ear is stimulated. Neff and Casseday (1977) found that after a unilateral ablation of the auditory cortex contralateral to the intact stimulated ear, a cat was unable to localize sound with the intact ear.

Jenkins and Merzenich (1984) found that small unilateral lesions in the AI portion of the auditory cortex within areas representing limited bands of frequencies led to loss of the ability to localize sounds within these frequency bands in the auditory space contralateral to the lesions. In addition, they found that a cat with a massive unilateral lesion sparing only a narrow frequency band within the AI lost the ability to contra laterally localize sounds of all frequencies except those located in the spared tissue. They concluded that "the AI is organized to represent the contralateral hemifield of auditory space and that this spatial organization occurs within frequency representation channels."

These findings indicate that the localization function occurs in the hemisphere contralateral to the sound source and that it is a function specific to certain areas of the auditory cortex.

While lesion studies provide a partial picture of auditory function, they are somewhat difficult to interpret because the structure of the cortex is altered. The lesions may be affecting far more than the studies are indicating. Two newer, non intrusive techniques have been developed to investigate cortical activity in humans: Neuromagnetic responses and evoked potential responses.

Neuromagnetic Studies

The organization of the auditory cortex can be examined by manipulating sound parameters (i.e., frequency, intensity) and measuring the resulting changes in the magnetic response of the auditory cortex. In neuromagnetic studies, the magnetic field generated by currents due to differences in the electrical potentials of neurons activated by discrete stimuli is measured. They are measured by devices called SQUIDs

(Superconducting Quantum Interference Devices) which are placed against the surface of the skull and, unlike surface electrodes, are able to detect activity directly in the immediate neighborhood of the device. This is because magnetic fields, unlike electrical fields, easily penetrate the skull and are not affected significantly by the conductivity of the materials which surround the active region of the brain. Both the direction and magnitude of the neuromagnetic fields vary as a function of stimulus manipulations. The location of sources of the neuromagnetic fields are also observed to change as a function of stimulus manipulations. The auditory cortex can thus be investigated by manipulating the frequency and intensity of auditory stimuli and examining the evoked magnetic responses.

Frequency. Romani, Williamson, Kaufman, and Brenner (1982) presented steady-state stimuli of varying frequencies and found that the location of the source of the magnetic response changes as a function of changing stimulus frequency. Elberling Bak, Koford, Lebech and Saermark (1982) presented tone pips of various frequencies and also observed a posterior shift in the source of activation as a function of frequency change. Pantev, Hoke, Lutkenhomer and Lehnertz (1989) presenting tone burst stimuli of varying frequency found not only a posterior shift of source as a function of frequency change, but also an increase in depth of 8 mm in a frequency change from 500 to 4000 Hz. These studies imply that different neurons are involved in the response to different frequencies and that the neurons responding to higher frequencies are located more posteriorly, perhaps deeper, in the auditory cortex than those responding to low frequencies.

Intensity. The magnetic response is also sensitive to intensity. Elberling (1981) found that when the magnetic field responses to tone bursts varying from 30 to 80 dB are measured, the amplitude of the response assumed a maximum up to 60 dB and declined as stimulus intensity was increased. The latency of the response exhibited a flat minimum at 60 dB. An increase in stimulus intensity resulted in a slight increase in latency. Pantev, Hoke, Lehnertz and Luthenhoner (1989) using the same stimuli investigated the location of the source of the magnetic response as a function of stimulus intensity. It was found that the source of the activity became shallower as the intensity of the evoking stimulus became greater.

The preceding results show that while the latency of a magnetic waveform varies little with stimulus intensity, both the amplitude of the magnetic waveform and the source of activation in the auditory cortex does change as a function of stimulus intensity. This implies the neural populations activated by a stimulus change as the intensity of the stimulus changes. Neural populations responding to intensity of sound do so in a specific manner. Intensity is not represented by one large non-specific intensity population. Rather, the neurons encoding intensity seem to be organized in an amplitopic fashion with specific intensities activating specific neural populations.

Evoked Potential Studies

The evoked response of the brain generates both magnetic and electric fields when presented with a stimulus. The magnetic field is detected using a SQUID as discussed previously. The electric field evoked to the stimulus is manifested as a potential difference between electrodes placed on the surface of the head.

The evoked potential developed between these electrodes has a characteristic time-varying response which is transient in nature. The details of the shape of this complex waveform have been studied extensively.

The averaged evoked potential (AEP) is a representation of the brain's electrical response to discrete stimuli and is composed of a series of positive and negative peaks. The amplitude and latency of these peaks have been studied extensively as indicators of brain activity, both cognitive and physiological. The auditory evoked potential consists of P1 (first positive deflection at approx 50 ms), N1 (first negative deflection at approx 100 ms), P2 (second positive deflection at approx 175 ms), N2 (second negative deflection at approx 250 ms), and P3 (third positive deflection at approx 275 ms) (Figure 1). Because they are maximally responsive to changes in stimuli, N1 and P2 are usually the focus of non-cognitive studies involving manipulations of exogenous stimuli. This is the case in the following studies.

Insert Figure 1 about here

Frequency. Organization of the auditory cortex has been examined using evoked electrical potentials. As with the magnetic wave studies, the sound parameters of the stimuli are varied and the ensuing changes in the evoked potentials are measured and interpreted based on what sound manipulations were performed. In a study designed to investigate the organization of frequency and sound localization functions in the auditory cortex, Butler (1972) presented tones of 375, 1000 and 8000 c/sec paired with a tone of 250 c/sec. The purpose of the experiment was to determine whether the evoked response to the 250 c/sec tone would change in amplitude as a function of the tone with which it was paired. It was hypothesized that the closer the frequency of the paired tone to 250 c/sec, the smaller would be the amplitude of the potential evoked by the 250 c/sec tone. This was explained in terms of limited resources and periods of adaptation. Certain neuron populations would respond to a tone of 375 c/sec. Some of those neurons would also be part of the response when a tone of a similar frequency was presented (250 c/sec). These previously activated neurons would still be in a period of adaptation and would not be able to contribute to the response to the second tone, leading to a response smaller in amplitude than when all neurons are firing. The farther apart the frequencies of the tones, the fewer the common neurons involved in the responses. If the neurons had not been previously activated, they would not be in a refractory period and all neurons would be responding, leading to an N1-P2 response of full amplitude. Therefore, the response to a 250 c/sec tone when preceded by a 350 c/sec tone would be smaller than the response to a 250 c/sec tone preceded by an 8000 c/sec tone. This is what Butler found. He concluded that "the data support the notion that the auditory cortex is organized tonotopically but that each tonal frequency has widespread neural representation"(pg 281).

Further support for tonotopic organization of the auditory cortex comes from Picton, Woods, and Proulx (1978) who presented trains of tones of identical frequencies with occasional intervening tones of a different frequency. The closer the frequency of the intervening tone to the frequency of the tone train, the smaller was the amplitude of the N1 response to the intervening tones. As the frequency separation between the tone train and the intervening tone increased, so did the amplitude of the N1 response to the intervening tone.

Naatanen, Sams, Alho, Reinikainen, and Sokolov (1988) found that when tones of identical frequencies are presented in sequence, a smaller N1 is generated than when tones of different frequencies are delivered in sequence. In a study similar to Picton et al (1978), Naatanen et al. (1988) found a significant frequency specificity effect. Again, the closer the tone train frequencies to the intervening tone frequency, the smaller the evoked response to the intervening tone and vice versa. The larger the frequency difference, the larger the amplitude of the evoked response.

These studies demonstrate the involvement of specific overlapping neural populations in specific frequency processing and again show that the farther apart the frequencies to be processed are, the fewer the neurons the frequency processing space will have in common.

Location. Butler (1972) found results similar to those found on frequency specificity in an investigation of the location specificity of neural functioning. Tone trains of constant frequency were presented from locations of 270 azimuth. Intervening tones of the same frequency were presented from locations of 270 to 90 azimuth. The closer the location of the source of the intervening tone to the location of the source of the tone train, the smaller the amplitude of the response to the intervening tone. The amplitude increased as a function of increasing source separation up to about 90^{0} . After that, the effect was negligible.

Naatanan (1988) in an attempt to determine whether the generators for frequency and spatial location were distinct, presented subjects with tone trains of 1000 Hz subjectively located in the middle of the head. Intervening tones differing in frequency and/or location from the tone train were also presented. The study was designed to present both a change in location and in frequency to determine first, whether the amplitude of the response changed as a function of the frequency separation or the distance of the location change and whether these two parameters interacted in any way in their effect on response amplitude. Naatanan replicated Butler's (1972) results, finding the amplitude of the response to intervening tones increasing as the frequency separation between tone trains and intervening tones increased. The location effects were slightly different from Butler's. The strongest effects (i.e. the largest amplitude to intervening tones) were found when the tone trains and the intervening tones were presented to different ears. No interaction was found between frequency and location effects. The conclusion was that the location sensing neurons were separate for each ear and those were separate from the frequency sensing neurons.

Location sensing neurons appear to be less distinct from each other than are frequency sensory neurons except in the case of lateralization (left ear vs right ear). Right ear generated responses appear to have few neurons in common with left ear generated responses. Picton et al. (1978) concluded after presenting tones monaurally, that the generators of the N1 component activated by presentation to each ear are to a great extent separate and distinct.

MMN. A slightly different area of evoked potential research which also gives some insight into cortical organization is that of the mismatch negativity wave (MMN). An MMN is a slow negative deflection that occurs in the response to a deviant stimulus. MMN has been elicited by deviations in frequency or intensity of stimulus (Naatanen, 1978; Naatanen & Gaillard, 1983). Naatanen and Picton (1987) explain MMN as occurring when a comparison of a neural memory trace of the standard stimulus does not match up with the perception of the deviant auditory stimulus. This explanation assumes that the activation of sensory neurons continues for a short time after their initial stimulation, an idea analogous to the parameterization of motor programs remaining activated for a short period after the program has been initiated. In Paavilainen, Karlsson, Reinkainen, and Naatanen (1989) it was demonstrated that localization of sound as well as frequency and intensity can elicit an MMN. Subjects were presented standard tones from one location and tones that were deviant only in their location relative to the standard ones. These deviant tones elicited an MMN. According to Naatanen and Picton (1987) this would mean that the neurons involved in the localization of the standard stimuli remained excited for a time after their activation and that a separate set of neurons was responsible for the localization of the deviant stimulus. The comparison of the separate neuron activations led to the elicitation of an MMN. This implies that the neurons responsible for localizing sound are a) organized in neural populations and b) that these neural populations can be primed for a time after initial activation.

The overall picture presented by the evoked potential studies of the auditory cortex is one of a series of overlapping neural populations, some of whose members respond to certain specific frequencies and to closely separated frequencies. The above studies present the auditory cortex as organized tonotopically and amplitopically and somewhat according to localization function. Given this organization of the auditory cortex, sensory switching and repetition can logically be investigated by repeating or changing sound parameters and measuring the electrical responses to those changes. If specific neural assemblies can be activated by specific sound parameters, perhaps the response of those neural assemblies involved can be primed or changed by repeating or changing the evoking sound parameters. This is the basis for the following study.

Thomas and Whitaker (1990) designed an evoked potential study based on the tonotopic organization of the auditory cortex to test whether the switching time and repetition effects seen in the motor realm were also present in the sensory realm. Subjects were presented with a series of three tones called triplets. These triplets were constructed from a combination of low tones (L), medium tones (M), and high tones (H) with the stipulation that the first two tones were identical to each other and the third tone would be either the same as the first two (Same condition), a 65 Hz change (1-step condition), or a 130 Hz change (2-step condition). All subjects therefore received nine different triplets (LLL, MMM, HHH, LLM, LLH, MML, MMH, HHL, HHM) randomized in 30 blocks for a total of 270 trials. Subjects were asked to indicate with a button press whether the third tone was the same as the first two or different from the first two. The experimental question was, would the latencies of the evoked responses to a tone change as a function of whether the tone was a repetition or a change in the frequency of the previous tone? The processing time of the stimulus was assumed to be reflected in the latency of the evoked potential to that stimulus. Using a neural model of overlapping neural space with similar stimuli exciting some common neurons, and keeping in mind the sensory and motoric studies which found repeated stimuli took less response time than changed stimuli, it was hypothesized that the latency of the response to the second tone would decrease from the latency of the response to the first tone. This was due to the supposition that the two responses would have all neurons in common and that those neurons would be parameterized for the second response by the first response. Therefore, the parameterization step would be skipped for the second response thus saving some time. This was indeed demonstrated in Thomas and Whitaker (1990). The mean latency decrease of N1 from tone 1 to tone 2 was 13.1 ms. This change did not differ significantly across conditions (Same, 1-step, 2-step) which was expected since the first two tones were identical across conditions.

The second part of the hypothesis involved comparing changes from tone 2 to tone 3 in the three different conditions. Again, using the neural and motoric models already explained, it was expected that the change from tone 2 to tone 3 in the Same condition would be less than the change from tone 2 to tone 3 in the 1-step condition which in turn would be less than the change from tone 2 to tone 3 in the 2-step condition. These predictions were made because it was thought that a repetition in stimulus would lead to either no change or a decrease in latency from tone 2 to tone 3 because all neurons were common to the responses and hence, already parameterized. The 1-step change would lead to a change in neural space and a decrease in the number of neurons commonly stimulated and parameterized, and a 2-step change would exacerbate these conditions even further leading to an increase in processing time and hence the latency of the evoked response (a switching time effect). The hypothesis was in the main supported. The latency of N1 remained about the same from tone 1 to tone 2. The latency of the evoked response from tone 2 to tone 3 in the Same condition decreased while the latency from tone 2 to tone 3 in the 1-step condition and the 2-step condition increased. However, there was no significant difference between the changes in the 1-step condition and the 2-step condition. The main conclusions of the study were that there was a sensory switching time effect and a sensory repetition effect analogous to those found in the motor realm, and that the switching time effect was a centralized, digital one not dependent on the size of the separation between frequencies.

The previous paragraphs cite several evoked potential studies which investigated latency and amplitude of N1 as a function of stimulus manipulation. These measures are traditional ways to investigate brain processes using the evoked potential wave. However, recent investigations of the evoked potential wave have revealed that the N1 deflection of the wave cannot be analyzed or interpreted as a single component. It must be viewed as a manifestation of as many as six components that vary in occurrence and form with the conditions of stimulus and subject (Naatanen & Picton, 1987). Naatanen and Picton (1987) describe three of these components as exogenous, or tied to characteristics of the stimulus, and three as endogenous, or tied to the state of the subject. They base this theory on source analyses of N1 and on comparisons of neuromagnetic measurements to electrical measurements of brain events.

Source Analysis

The source analysis studies are done in two ways: In one, electrodes are placed all over the head and the distribution of the evoked potential is mapped. This technique is used to show if some areas are more active than others during stimulus presentation and if some areas show different latencies of response. It is thought if N1 were a manifestation of a single source activation, one could expect the response to appear the same at every electrode site because of the conduction properties of the brain, brain fluid and skull. The distributions obtained from these multiple electrode sites provide maps of the fields of the activity generated by a single stimulus. From these maps, dipole sources of the activity are postulated (Scherg & von Cramon 1986). More than one source for the activity generating N1 would imply more than one component to N1 (Wood & Wolpaw, 1982; Scherg & von Cramon, 1985). It has been concluded from these analyses that multiple generators for N1 are most likely.

The second means of source analysis involves obtaining difference waves between electrode sites. These difference waves are the response unique to a particular site. If difference waves between electrode sites occur, then not all electrode sites are recording the same response. Wolpaw and Penry (1975), Wood and Wolpaw (1982), McCallum and Curry (1979), and Perrault and Picton (1984) used this technique and their findings support the postulate of multiple generators of the N1 response.

Comparisons of Magnetic to Electrical Measurements

The logic for the comparisons of electric to magnetic measurements is as follows: When a current dipole is activated, the electrical field generated is very different from the magnetic field (Cuffin & Cohen, 1979). The ways in which the fields propagate from the source are quite different. The surface measurements are also different. The surface measurement of the electrical field is dependent on the conductivity of the fluids and solids surrounding the source, and is a more global, composite measurement than the magnetic measurement. The magnetic measurement is more specific to source (Grynozpan & Gesolowitz, 1973). However, both fields are the result of a dipole source responding to a discrete stimulus within a prescribed period of time. Therefore, when compared, they should show the same latency of response if the source of the electrical and magnetic responses are the same.

Using such comparisons, Reite, Zimmerman, Edrich and Zimmerman (1982) found differences in latency between magnetic and electrical responses to the same stimuli. Because the electrical response is a more global response than the source-specific magnetic response, these studies suggest the two are measuring different sources of activation and support the idea of the electrical N1 having a component structure composed of the responses of different areas of activation.

Naatanan and Picton (1987) in an extensive review of the above techniques conclude that there are three exogenous components which contribute to the N1 deflection of the electrical evoked potential wave: Component 1 is a specific auditory processing component coming from a vertical dipole located in the cortex of the supratemporal plane. The logic for its existence comes from magnetic recordings which suggest a dipole vertically oriented at the level of the supratemporal plane and sensitive to auditory stimulus onset and offset, (Hari, Aittoniemi, Jarvinen, Katila, & Varpula, 1980), frequency, (Elberling, Bak, Kofoed, Lebech & Saermark, 1980) and intensity (Bak, Lebech, & Saermark, 1985).

Component 2 is described as a biphasic component generated in the auditory association areas and is revealed by obtaining difference waves between the vertex electrode and the mid-temporal electrodes (Wolpaw & Penry, 1975; Wood & Wolpaw, 1982; McCallum & Curry, 1979; Perrault & Picton, 1984).

Component 3 is the least understood exogenous component. Because the scalp distribution of the N1 response depends on the ISI (interstimulus interval) used in stimulus presentation and because the magnetic N1 recovers at shorter ISI's than the electrical N1, (Hari, Karla, Katila, Tuomisto & Varpula, 1982), Naatanen et al. (1988) proposed that component 3 is timing-sensitive and reacts differently to frequent and infrequent stimuli.

The three exogenous components postulated for N1 as well as the logic for that postulate have been discussed. Two of the other three components thought to contribute to N1 are subject state dependent and can be evoked through subject state manipulation. Since the present study did not involve any of these state manipulations, the endogenous components are not discussed. The N1 component, MMN discussed previously, seems to have both exogeneous and endogenous traits.

Component 1, a specific auditory processing component maximally recorded frontocentrally; component 2, a biphasic component maximally recorded midtemporally; and component 3, a non-specific component sensitive to ISI and maximally recorded from frontocentral and vertex electrodes are the three stimulus dependent N1 components which were addressed in the following study. The study involved placing electrodes at frontocentral, vertex and midtemporal sites in order to maximally record each of the three components and in order to use difference waves and other signal processing techniques to determine the unique contribution of each site's activity to the whole N1 deflection. ISI was also varied in order to investigate differences in response between ISI's. This was to help determine the relative contribution of the ISI sensitive component to the whole N1 deflection.

Statement of the Problem

The preceding review has presented a behavioral effect known as the switching effect in which repeated output takes less production time than alternating output. The switching effect has also been demonstrated in the sensory realm as a decrease in reaction time to repeated stimuli and an increase in reaction time to changed stimuli. The present study investigated the underlying neural activity occurring when subjects were presented with repeated stimuli and when they were presented with changed stimuli. The stimuli used were pure tones. It was hypothesized that these pure tones would activate neurons in the auditory cortex. This activation was measured using evoked electrical responses of the brain. Because these responses are a result of neural activity in response to discrete stimuli, the evoked response latencies were measured to indicate the real time occurrence of the neural activity. It was hypothesized that if the switching effect were manifested at the neural level the latencies of the evoked responses would change in the following ways: 1) The latencies of the responses to repeated stimuli would remain the same or decrease as do the reaction times to repeated stimuli in behavioral studies. 2) The latencies of the responses to changed stimuli would increase as do the production times of changed motor outputs in behavioral studies.

Before the above problem was investigated, a signal analysis was done on the evoked responses because literature indicates that the peak of the signal to be used in latency measurements (N1, the first negative deflection of the evoked response signal) may actually be a compilation of as many as six components. The signal analysis was done to help to separate and identify these components. After the signal analyses were performed, the above hypotheses were tested using the analyzed signals. The following Methods section explains how the signal analysis was done and how these analyzed signals were used to investigate the neural activity underlying the switching effect.

Methods

The present study used standard signal analysis to investigate the structure of the N1 deflection of the average auditory evoked potential wave. N1 was targeted because of its exogenous nature and because it showed the most robust effect in the Thomas and Whitaker (1990) study of sensory switching. The present study also examined whether the latency and amplitude of N1 or of its components change as a function of frequency change of the auditory stimulus. The influence of interstimulus interval (ISI), order of evoking stimuli, and recording site were also examined.

Because of its possible multiple component structure, the N1 signal must first be analyzed for components to form a basis to interpret latency and amplitude measurements. If the evoked response contains components which vary in latency and amplitude, the components may be representative of different sources or independent processes that are being evoked by a stimulus and their sum latencies and amplitudes would reveal nothing of these complex underlying processes. The net amplitude and resulting latency would not represent a single, simple physical process; thus a change in latency of a net N1 wave may represent true phase shifts of all components or it may be a reflection of the sum of varying phase shifts and amplitudes among components and reveal nothing about timing or strength of a single underlying process.

The first part of the present study was a pilot of signal analyses techniques and involved examining previously collected evoked potential data to determine whether an ISI-sensitive component of N1 could be discerned. The data were collected in four different studies over a period of three years to investigate a phenomenon known as "fast habituation." Fast habituation is the attenuation of the average evoked potential (AEP) amplitude that generally occurs to the second stimulus in a pair of stimuli separated by an interstimulus interval (ISI) of less than five seconds.

The second part of the present study further investigated the component hypothesis and the switching effect by gathering new data in a paradigm which varied both ISI and electrode site. The methods for the signal and statistical analyses are discussed later in detail. The following methods are for part two of the present study.

Subjects

Six of the eight subjects were recruited from the Introductory Psychology course at Oklahoma State University and were 18-23 years old. They received extra credit in the psychology course for their participation in the study. Two of the eight subjects were friends of the experimenter, were 33 years old and received no compensation for participation. All were free of hearing and neurological deficits. Two of the subjects' data were not used because of excessive artifact. All analyses were done on six rather than eight subjects.

Materials

Stimuli for Experiment 2 consisted of tone pips (200 ms, 76 dB SPL, 2 ms rise time) of two different audio frequencies, 265 Hz (low or "L") and 395 Hz (high or "H"). The tones were arranged in sets of four (quadruplets). The first three tones were the evoking stimuli; the fourth in the set was not analyzed and acted only as a means of evenly focusing subjects' attention on the stimuli. The fourth tone was needed because previous studies have found a large, late-occurring peak in responses that occur to stimuli that require a decision on the part of the subject. This late-occurring peak may be a complication in analyzing N1. Therefore, the first three tones had no particular decision-making tasks associated with them. The fourth tone had a decision-making task associated with it and was most likely to have a late-occurring peak. Thus, only the responses to the first three tones were analyzed. The tones were arranged so that the first two tones of the set were identical to each other and the third and fourth ones were either of the two possible frequencies. These arrangements were LLLL, LLLH, LLHL, LLHH, HHHL, HHHH, HHLL, HHLH. Pilot analyses indicated no significant differences between waveforms evoked by high frequency tones and those evoked by low frequency tones. Therefore, the evoking stimuli were placed in four arrangements in which the three evoking stimuli were the same frequency (Same) and four arrangements in which the evoking stimuli changed frequencies on the third tone (Different). These arrangements allowed for the most efficient testing of the switching effect by providing responses to repeated and to changed stimuli.

There were three ISI conditions: 300 ms between tones (short), 800 ms (medium) between tones and 1000 ms (long) between tones. The interval between quadruplets of tones was a minimum of 6 s. The ISI between tones, the frequency of the third tone of the evoking stimuli, the order of the evoking stimuli and the recording site were the factors in a four factor design. ISI has three levels (300 ms, 800 ms, 1000 ms), frequency has two (Same and Different), stimuli order has three (tone 1, tone 2, tone 3), and recording site two, (CZ, FZ).

As shown in Figure 2, for the 300 ms ISI, data collection began 300 ms prior to Tone 1 which was presented for 200 ms. Tone 2 onset was at 800 ms (300 ms after Tone 1 offset) and offset was at 1000 ms; Tone 3 onset was at 1300 ms (300 ms after Tone 2 offset) and offset at 1500 ms; Tone 4 onset was at 1800 ms (300 ms after Tone 3 offset) and offset at 2000 ms. For the 800 ms ISI, data collection began 300 ms prior to Tone 1 which was presented for 200 ms. Tone 2 onset was 1300 ms (800 ms after Tone 1 offset) and offset at 1500 ms; Tone 3 onset was 2300 ms (800 ms after Tone 2 offset) and offset at 2500 ms; Tone 4 onset was at 3300 ms (800 ms after Tone 3 offset) and offset at 3500 ms. For the 1000 ms ISI, data collection began 300 ms prior to Tone 1 which was presented for 200 ms. Tone 2 onset was at 1500 ms (1000 ms after Tone 1 offset) and offset at 1700 ms; Tone 3 onset was at 2700 ms (1 s after Tone 2 offset) offset at 2900 ms; Tone 4 onset was at 3900 ms (1 s after Tone 3 offset) offset at 4100 ms.

Insert Figure 2 about here

Procedure

Each subject was seated in a comfortable chair in a shielded room and informed consent was obtained. Electrodes were affixed to the scalp at the vertex (Cz), frontal (Fz) and temporal (T3/T5) sites and referenced to linked ear electrodes. Eye movements were monitored by electrodes placed above and to the left of the left eye. Electrode impedances were kept below 5 Kohms. The EEG was recorded through gold plated disc electrodes and amplified by a Grass Model 79 polygraph with band passes of 0.3 to 100 Hz with 60 Hz notch filters.

The lights were dimmed and subjects were instructed to relax. They were told to listen to the tone quadruplets and to press a switch held in one hand if the fourth tone of a quadruplet was the same as the third, and to press a switch held in the other hand if that fourth tone was different than the third one. The hand used for responding was counterbalanced across subjects.

A trial was initiated by the experimenter when the subject was relaxed and not moving and the EEG and eye movement channels were artifact free. A trial was rejected and replaced if eye movement artifact exceeding 75 μv occurred at any time during the data collection.

Data Reduction

Data from 15 artifact free trials for each triplet were averaged (only data from the first three tones were analyzed). The 60 trials from the triplets in which the third tone was the same as the first two (LLL, HHH) were averaged together within ISI as were the 60 trials from the triplets in which the third tone was different (HHL, LLH) to yield 6 evoked potentials (EPs) per subject [3 tones x 2 conditions (same and different)], per ISI, for a total of 12 EP's per subject per electrode (6 per ISI x 3 ISI's). The net N1 wave is the negative deflection appearing from 50 to 150 ms after stimulus onset (Figure 2).

For the analyses, T1 (the response evoked by tone 1), T2 (the response evoked by tone 2) and T3 (the response evoked by tone 3) as well as the changes from T1 to T2, T2 to T3 and T1 to T3 were compared within and between conditions (SAME and DIFF), within and between ISI's (Short, Medium, Long) and within and between electrodes (CZ, FZ) to determine whether ISI- or electrode-dependent components could be discerned in the evoked potential waveform. Data recorded from the temporal electrode were very noisy and difficult to interpret, therefore, only data from CZ and FZ were analyzed and compared.

Signal Analyses

The component structure of the N1 deflection of the auditory evoked potential wave must first be determined in order to relate the behavior of N1 as a function of stimulus frequency change to a single process. In order to determine the possible influence of components, the evoked potential waveform was analyzed using computer-based signal analysis software. The characteristics of the waveform were determined using a commercial graphical spreadsheet offered by DSP Development Corporation. It was run on an IBM personal computer. The software was programmed using high-level commands to use resident programs to perform signal analysis in the form of graphical or numeric displays. The software was programmed to perform a standard signal analysis routine on imported evoked potential data and record the formatted results in milliseconds.

The first question addressed by the analyses concerned the switching effect. Since the SAME condition had no change in stimulus frequency from T2 to T3 and the DIFF condition did change in stimulus frequency from T2 to T3, significant differences between the SAME and DIFF conditions were evaluated. Comparisons between the latencies for these two conditions are addressed in the results section.

The second question to be considered by the analyses was, could ISI- or recording site-sensitive components be discerned in the evoked potential waveforms? This was addressed by performing both qualitative and quantitative analyses on each signal.

The qualitative analyses included overplots, difference waves and power spectral distributions. The quantitative comparisons involved measuring latency, amplitude and energies of the N1 peak of each signal and then statistically comparing these measurements in an ANOVA and in a Dunn's analysis of individual comparisons . A detailed explanation of the type of analysis used to evaluate the latency, shape, and energy in the observed evoked potential response follows. There are six procedures used in evaluation.

Overplots. Overplots of the evoked voltage as a function of time were used to compare the following: T1 to T1, T2 to T2, T3 to T3, T1 to T2, T2 to T3, and T1 to T3. If the shapes of the signals were identical, the signals lay on top of each other. If the signals were not the same shape, differences can be discerned through the overplots.

Difference Waves. The goal of examining difference waves was to determine the shape differences between signals. There are other more efficient means that were used to determine size differences between signals (amplitude and energy measurements). Because size differences were not of interest in this particular analysis, the original signals were normalized before they were subtracted. The normalization function follows:

$$\text{Normalized } V(t) = V(t)/\text{maximum value}$$

This made the amplitude of the most extreme point on all the signals (N1) equal to 1 and helped to ensure that any effects seen in the difference waves would be shape differences not size differences .

The signals were made up of 500 discrete points. When responses were compared, each point of one signal was subtracted from the corresponding point of the other signal. The resulting 500 point signal was the difference wave. This difference wave is a representation of that part of one signal that is not held in common with the other signal. A difference wave with a large amplitude means the shapes of the two compared signals were very different. A difference wave with a small amplitude signifies that the shapes of the two signals that were compared were very similar.

Power Spectral Distribution. The power spectral distribution (PSD) shows the frequency (Hz) distribution of the energy of the signal. It extracts the frequency components that make up the signal by providing a Fourier analysis of the squared amplitude of the signal. The analysis of the squared signal yields a single distribution as a function of frequency.

The procedure in the present study involved extracting the first 200 data points of the signal. This was due to the importance of the N1 feature found in the first 200 points. A Hanning window was then placed on the signal. The Hanning window allows the signal to gradually approach zero from the end data point rather than having a sharp drop-off from the end point to zero. This is desirable because a sharp drop-off in a signal leads to false high frequency components in the spectral distribution. A sharp drop-off can also lead to "aliases", false repetitions of the signal placed end-to-end in the Fourier analysis. Analysis of the aliases can lead to an incorrect distribution. The Hanning window eliminates false high frequency components and aliases.

After the Hanning window was applied, the signal was padded. Padding adds zeros to the beginning and end of the signal. It has no effect on the signal, but is a mathematical procedure which increases the density of points available to the PSD and hence increases the resolution of the PSD.

The resulting distribution was then normalized so that the maximum point was equal to one. This was done so all frequency distributions could be compared on the same scale. No important information was lost because the relative, not the absolute sizes of the frequency components were important. The power spectral distributions of different responses were then compared.

Latency comparisons. The latency (occurrence in time) of the minimum point of the N1 peak was measured. The latencies of the relevant responses were then compared.

Amplitude comparisons. The voltage of the minimum point of the N1 peak was measured. The amplitudes of the relevant responses were then compared.

Relative Energy comparisons. The signals were squared to remove the negative components. The area of the squared signal was then measured (A). The area of the squared signal is proportional to the energy of the signal. This can be seen in the following equation:

$$\text{Energy} \propto A = \int v^2 \, \mathrm{d}t$$

where v is equal to voltage and t is the time increment of the signal. For this reason, A is directly proportional to the energy of the signal for all the measurements for a single subject. The energies of the relevant responses can then be compared for that subject.

Statistical Analysis

The design for the second study was a 2 x 2 x 3 x 3 incomplete factorial. The conditions were Frequency (Same, Different) x Electrode Site (CZ, FZ) x Tone (tone 1, tone 2, tone 3) x ISI (short, medium, long).

An analysis of variance was done on the quantitative measurements (latencies, amplitudes and energies) of the N1 deflection of the evoked potential. The analysis of variance was used to obtain a pooled error term for Dunn's multiple comparison tests. There were four main hypotheses to be tested with six contrasts performed for each hypothesis. At the .05 probability level, using the Dunn's test, the critical amplitude difference was 6.25. The critical energy difference was 11,103, and the critical latency difference was 11.3. The results of the statistical and signal analyses follow.

RESULTS

The independent variables in the study were electrode site (CZ, FZ), interstimulus interval (short, medium, long), and condition (SAME, DIFFERENT). In the following, results are presented for which all tones were compared to each other within and between electrode sites, within and between interstimulus intervals (ISI's), and within and between conditions (Figure 3).

Insert Figure 3 about here

Both the qualitative comparisons- overplots, difference waves, and power spectral densities (Figure 4),- and the quantitative comparisons- N1 latency, and amplitude and signal energy comparisons of the first 200 data points (first 200 ms) (Figure 5)- follow.

Insert Figures 4 and 5 about here

These analyses allow full investigation of both the latency change hypothesized by the switching time hypothesis, and the influence of timing and electrode recording site on the evoked response signal.

Within Electrode, Within ISI, Between Conditions

The tone comparisons under this heading investigated both the switching effect hypothesis and the component hypothesis. The question addressed was, were there any qualitative or quantitative differences in the evoked response between conditions (SAME, DIFF)? The quantitative analyses (latency, amplitude, relative energy comparisons) yielded no significant results between conditions. However, the PSD profiles revealed differences between T3 SAME and T3 DIFF in their responses as a function of ISI. The PSD profiles of T3 SAME and T3 DIFF showed a 3 Hz peak and a 10 Hz peak . In SAME, the 3 Hz peak decreases in size with increasing ISI while the 10 Hz peak increases in size with increasing ISI. In DIFF, neither peak varies much as a function of ISI (See specifics and figures under Power Spectral Density section).

Within electrode, Within ISI, Within Condition

Tone comparisons within electrode, within ISI, within condition, investigated the influence of the order of the stimuli on the evoked response when no other parameters were changed. Because the second tone was the same frequency as the first one, it was expected that the shape of the N1 deflection of the ERP generated by the two tones would be the same. In the first major comparison, the shapes of T1 and T2 were compared. It was hypothesized that if the shapes were the same, it could be assumed that components of N1 were responding in phase with each other, that changes that occurred in latency and or amplitude of N1 were occurring in all N1 components at the same time, and there were no phase shifts among components which may have shown up as false latency or amplitude changes in the sum N1 deflection. However, if the shapes of the N1 deflections to tone 1 and tone 2 were different, it could be assumed that all N1 components were not responding identically to amplitude and in phase.

The second major shape examination within ISI was that of comparing T2 to T3 when the evoking tones were the same frequency and when they were different frequencies. In the Same condition, it was predicted that when no stimulus changes were made, no shape differences would occur between the N1 evoked by tone 2 and that evoked by tone 3 because the stimuli were identical but for their relative positions in the stimulus presentation. In the DIFF condition, some differences in response between T2 and T3 were expected because the audio frequency of the stimuli change from T2 to T3. If the neural responses were analogous to the behavioral responses found when investigating the switching effect, the change in stimuli frequency was expected to lead to a longer response time (latency) of the brain's evoked response. The change in stimulus frequency could also be expected to produce a change in other signal characteristics such as PSD profiles, energy, and amplitude.

A third comparison under this heading would be that of T1 to T3 when the evoking tones were the same or different frequencies. Again, no change in stimuli parameters were expected to yield no change in response parameters while the change in frequency from T1 to T3 in the DIFF condition was expected to yield some response differences.

The switching effect hypothesis that change in stimulus parameters (tone frequency) would lead to differences in response latencies was not supported. However, there were differences in the PSD profiles of the signals as a function of stimulus auditory frequency. There were also significant quantitative changes in responses as a function of the order of the evoking stimuli, i.e., T1 amplitude was significantly different from T2 amplitude in the same condition and the same ISI.

As measured from CZ and FZ, T2 was significantly different from T1 in amplitude, energy, shape and energy spectral densities (PSD) in the medium and long ISI's. There were no significant quantitative differences between T2 and T3, but their PSD profiles were different. As measured from CZ and FZ, T1 and T3 were significantly different in amplitude, shape, and PSD in the short ISI. They were also significantly different in amplitude, energy, shape and PSD in the medium ISI measured from CZ. T1 and T3 as measured from FZ in the long ISI were significantly different in amplitude, shape, and PSD.

Overplot. From both electrodes in all three ISI's, T1 showed a larger N1 and P2 response than either T2 or T3. T2 and T3 were very similar to each other (Figure 6).

Insert Figure 6 about here

Difference Wave. The difference waves between T1's in all ISI's are virtually flat as are the difference waves between T2 and T3 (Figure 7a and 7b).

Insert Figures 7a and 7b about here

However, the difference waves between T1 and T2 and between T1 and T3 reveal some fairly large deflections between 50 and 150 ms (Figure 8-11).

Insert Figures 8-11 about here

Because size differences between tones were removed, these difference waves indicate shape differences do exist between T1 and T2 and between T1 and T3. These findings are consistent with the PSD profiles of these responses and with the quantitative differences between these responses.

Power spectral density. The PSD profiles determine the amount of energy in each frequency component present in the evoked response signal. The PSD was analyzed as a function of both position of the stimulus in the stimulus sequence and the length of the interval preceding the stimulus.

As can be seen in Figure 12 and 13, in all ISI's, the T1 power spectral density reveals a large 9 Hz component and a small wide component at 16 Hz as measured from CZ SAME and DIFF. T2 in the short ISI has a large, sharp component at 3 Hz and a small wide one at 10 Hz. T2 in the medium ISI has a small component at 3 Hz, an equal-sized one at 10 Hz, and a very small component at 17 Hz.

Insert Figures 12 and 13 about here

In the long ISI, the T2 PSD profile contains a small component (smaller than that of the short and medium ISI signals at 3 Hz) at 3 Hz, and a larger wide one (also larger than the short and medium ISI peak at 10 HZ) at 10 HZ (Figures. 14 and 15).

Insert Figures 14 and 15 about here

In the SAME condition, in the short ISI, the T3 energy spectral densities show a large component at 3.0 Hz, a small component at 10 Hz and a very small component at 16 Hz. The 10 Hz component increases in size as the ISI increases and the 3 Hz component decreases in size as the ISI increases. In T3 DIFF, the 3 Hz and 10 Hz components only change slightly as a function of ISI (Figures 16 and 17).

Insert Figures 16 and 17 about here

The above changes in PSD varied consistently with ISI if T1 is categorized as the tone occurring after the longest ISI. In this way, it can be seen that the large component at 3 Hz in T2 and T3 in the SAME condition is largest in the short ISI and decreases in a regular way through the medium and long ISI's until it disappears in the very long ISI tone- T1 occurring after a 6-7 s ISI. In the same consistent way, the 10 Hz component seen in T2 and T3 SAME, increases from the short to the medium, to the long, to the very long ISI's.

In the DIFF condition, T2 again shows the progressive decreasing 3 Hz component with increasing

ISI, and an increasing 10 Hz component with increasing ISI. However, T3, the tone that is actually different, has a different profile from T3 SAME. The 3 Hz component decreases slightly with increasing ISI, and the 10 Hz component shows almost no effect as a function of ISI. This profile differs not only from T3 SAME but also from T2 SAME and DIFF in a way that T3 SAME did not.

The 15 Hz component shows an increasing trend of with increasing ISI with its largest manifestation in T1 which occurs after the longest ISI (6.03 s, 6.08 s, 7 s).

Amplitude comparisons. In the medium and long ISI's, the amplitude of the response signal changes as a function of the place in the sequence of the evoking stimulus and as a function of the length of the interval preceding the evoking stimulus.

In the short ISI, there were no significant differences between T1 and T2. In the medium ISI in both conditions (SAME and DIFF), and from both electrodes, there was a significant decrease in amplitude from T1 to T2 and from T1 to T3 (Table 1). This effect also occurred in the long ISI (Table 2). There was a significant decrease in amplitude from T1 to T3 in all ISI's including the short ISI as measured from both electrodes (Table 1-3).

Insert Tables 1-3 about here

Energy comparisons. T1 was generally significantly greater in energy than T2 and T3 in both the medium and long ISI's (Table 4 and Table 5). There were no significant differences in energy in the short ISI.

Insert Tables 4-5 about here

Within Electrode, Between ISI, Within Condition

Responses to tones of the same frequency and sequence position show different PSD, amplitude and energy characteristics as a function of the interval between the evoking tone and the preceding tone. The following results indicate that the evoked responses are affected by the length of the intervals between evoking stimuli and this may imply an ISI-sensitive component in the signal response. These comparisons were designed to discern ISI-sensitive components in the auditory evoked potential when electrode, condition and tone order were held constant.

As measured from CZ, T2 in the short ISI was significantly different from T2 in the medium ISI in amplitude, energy, shape and PSD. T2 in the short ISI was also significantly different from T2 in the long ISI in energy. As measured from FZ, T2 in the short ISI was significantly different from T2 in the medium ISI in amplitude, shape and PSD.

Amplitude comparisons. T2 in the short ISI was significantly larger in amplitude that T2 in the medium ISI. This was true in both conditions (SAME and DIFF) as measured from CZ, and in the SAME condition as measured from FZ (Table 6).

Energy comparisons. In both conditions (SAME, DIFF), T2 in the short ISI was significantly greater in energy than T2 in the medium and long ISI's. This effect was measured only from CZ (Table 7).

Insert Table 7 about here

PSD. The PSD profile of T2 reveals a 3 Hz peak and a 10 Hz peak in all 3 ISI's. However, the 3 Hz peak is large in the short ISI and gets progressively smaller through the medium and long ISI's, while the 10 Hz peak is a fairly consistent size for all three ISI's (Figure 14 & 15)

The difference between T1 and T2 was an order effect established earlier under the heading, Within Electrode, Within ISI, Within Condition. The following compared these differences to determine how they changed as a function of ISI. The changes in amplitude from T1 to T2 in the short ISI were significantly different from the changes in amplitude from T1 to T2 in the medium ISI. The change in amplitude from T1 to T2 in the short ISI was significantly different from that change in the long ISI.

Difference Waves. The difference waves between ISI's were virtually flat for T1 responses (Figures 18-20). T2 difference waves showed a large positive, negative deflection between 75 and 150 ms for short minus long and short minus medium (Figure 21 & 22). Medium minus long difference waves revealed little shape difference between the ISI's (Figure 23). The T3 difference waves revealed a shape difference between the short and long ISI's between 0 and 150 ms (Figure 24), and between the short and medium ISI's between 0 and 150 ms (Figure 25).

Insert Figures 18-25 about here

Amplitude comparisons-The change in amplitude from T1 to T2 was significantly greater in the medium ISI than in the short ISI. In the DIFF condition as measured from FZ, the change in amplitude from T1 to T2 was significantly greater in the medium ISI than in the long ISI (Table 8).

Insert Table 8 about here

Between Electrodes, Within ISI, Within Condition

These comparisons were designed to investigate the effect recording site had on the evoked potential waveform. ISI, condition and tone order were held constant in these comparisons. There were no significant differences between electrodes in any of the measured parameters.

Summary

There were no significant quantitative differences between conditions (SAME, DIFF) in any of the responses. The PSD of T3 SAME however, was different from the PSD of T3 DIFF as a function of ISI. No latency switching effects were found but the PSD profiles of T3 showed an interaction effect of ISI and condition.

The significant quantitative effects (amplitude, and relative energy) appeared as a function of the order of the tone stimuli and of the interstimulus interval between the tone stimuli.

The PSD profiles clearly show three frequency components to each evoked signal which change as a function of ISI, ISI and condition, and of order of the evoking stimuli. These results imply that there may be

ISI-dependent and order-dependent components to the evoked response and that there could be a switching effect manifested in the PSD profiles. The difference waves reveal shape differences between tones as a function as a function of ISI.

Discussion

The results of the present study clearly demonstrate "fast habituation" in the amplitude of N1, a manifestation of the multi-component structure of N1, and no switching effect in the latency of N1. These results are discussed below.

Fast Habituation

There is an attenuation in the amplitude of N1 from the T1 response to the T2 response in the medium and long ISI stimulus conditions. This attenuation in response has been reliably demonstrated in a number of studies (Callaway, 1973; Davis, Mast, Yoshie, & Zerlin, 1966; Wastell, Kleinman, & Maclean, 1982; Woods &Courchesne, 1986). Since in these studies, the amplitude of the peak was measured as either the voltage of the minimum point from baseline, or the difference in voltage between N1 minimum and P2 maximum, what was not clearly demonstrated in the cited studies was whether the amplitude attenuation equaled a true response attenuation or whether the apparent amplitude change was actually a result of a change in the shape of the response signal evoked by the second stimulus. The most obvious example of a shape change that would be manifested in an amplitude attenuation would be a widening of the N1 peak. This shape change would tend to pull the peak minimum point up closer to the baseline of the signal or to the maximum point of the next positive peak (P2) and would appear as a decrease in the amplitude of N1. The present study used potential energy measurements and difference waves in addition to amplitude measurements to more completely investigate "fast habituation" in N1. It was demonstrated that the amplitude attenuation in N1 from T1 to T2 corresponded to an energy attenuation from T1 to T2. There were no significant amplitude or energy differences between T2 and T3. in both the medium and long ISI's, there was also a shape change from T1 to T2 in the 0-150 ms range which is where N1 occurs in the evoked potential signal. There was little shape change from T1 to T2 in the short ISI.

The maximum attenuation in amplitude and energy was from T1 to T2. Stelmack, Michaud-Achorn (1985) also observed this effect. The attenuation in amplitude found in the present study from T1 to T2 in the medium and long ISI's corresponds to an attenuation in energy from T1 to T2 in these ISI's. However, in the short ISI (300 ms), there was no significant attenuation in either amplitude or energy from T1 to T2 and an attenuation in amplitude only from T1 to T3. This significant change from T1 to T2 in the longer ISI's and the lack of change from T1 to T2 in the short ISI would seem to contradict previous findings in this area (Davis, et al., 1966; Callaway, 1973; Wastell & Kleinman, 1982; Woods and Courchesne, 1986). It must be kept in mind however, that in these studies 500 ms was the shortest interval used and in most cases, the "short" ISI was 1 s long. None of these studies used an ISI as short as 300 ms.

A refractory period hypothesis has been advanced to explain the above findings. A simple refractory explanation would seem to dictate that the shorter the ISI, the fewer the neurons available from the first response to the second response, and the smaller the second response would be. As the ISI increases, more neurons would have time to become available from the first response to the second.

Some investigations into the attenuation of subsequent EP's have postulated the existence of a gating mechanism that exists in normal subjects and does not exist in schizophrenics (Freedman, Adler & Waldo, 1987; Waldo &Freedman, 1986). This gating manifests itself in reduced EP's, most specifically the P50 peak, but the reduction occurs throughout the signal. Freedman et al., (1987) say "The first stimulus is thought to "condition" or "activate" gating mechanisms which are tested by the second stimulus (pg. 223). This statement and the results of the present study imply that a mechanism more complicated than depleted resources could be involved in the reduction in response amplitude from the first response to the second. This mechanism could involve not simply a depletion of neural activity, but an active inhibition of neural activity. This inhibition would take a certain amount of physical time to occur and the short ISI of the present study (300 ms) may not be sufficient time for the inhibition or "gating" to fully develop. The medium and long ISI's do allow sufficient time for the inhibition. The fact that previous studies have shown an increase in attenuation with a decrease in ISI may be due to the lengths of the ISI's involved. Their "short" ISI's may be the ideal length of time for inhibition to fully occur and the longer ISI's involved could allow reduction of the inhibition effect leading to EP's of larger amplitude than those in the short ISI's.

In the present study, fast habituation occurred in both the amplitude and energy of N1 in the 800 ms and 1000 ms ISI's but not in the 300 ms ISI. Although a refractory period, depleted resources hypothesis has been one of the explanations advanced to explain fast habituation, the results of the present study imply a more active gating mechanism could be responsible. Single trial variability measurements and more measurements using extremely short ISI's are needed to further investigate this hypothesis.

Component Structure

One of the purposes of the present study was to ascertain, given the comprehensive signal analyses used, whether the evoked potential signal had a multi-component structure and if so, whether that structure had any influence on the single point latency and amplitude measurements of the entire N1 peak of the signal.

The PSD profiles of the various signals support a multi-component model of the evoked potential signal (Naatanen and Picton, 1987). Both the amplitude and the PSD of the signals change as a function of order of the tone stimuli. The frequency components present in the power spectral density of the response to tone 1 are different from those in the response to tone 2. There is a 3 Hz component present in the profiles of T2 and T3 that is not present in the profile of T1. This implies both quantitative and qualitative differences among the responses to the different tones.

As stated earlier, Naatanen and Picton (1987) postulated as many as six components involved in the structure of the evoked response signal. One of these components (component 1) is described as being sensitive to auditory features of the stimulus and another (component 3) as sensitive to timing information. An examination of the PSD profiles of the signals as a function of tone x ISI supports Naatanen and Picton's idea of a timing-sensitive component.

There is a 10 Hz and a 15-17 Hz component present in the PSD profiles of all three tones in all three ISI's and an additional 3 Hz component present in T2 and T3. The size of these components changes in a regular and consistent way as a function of tone and ISI. The 10 Hz component increases with increasing ISI while the 3 Hz component decreases with increasing ISI. The profile for each tone within an ISI is different from the other and these differences change as a function of ISI. This implies that stimulus position in a sequence of stimuli and timing of the presentation of those stimuli impact on the type of response given by the brain. The most likely candidates for the implied components are component 1 - sensitive to stimulus factors such as frequency, intensity, onset and offset, and presumably, sequence of stimuli, and component 3 sensitive to timing and ISI changes (Naatanen and Picton, 1987).

The PSD profiles indicated that N1 has a multi-component structure and the difference waves between tones and between ISI's indicated that these components may occur on different time scales. The difference waves indicated that the shape of T1 is different from the shape of T2 in the medium and long ISI's and that the shape of T2 and T3 differs as a function of ISI. This implies that changes in the minimum point latency and amplitude measurements of the average signal may not be measuring changes in the N1 peak as a whole but may be measuring variances in the occurrence of the components of N1. If the signal behaved as a whole or all N1 components occurred on the same time scale, qualitative changes such as shape changes would not occur from one response to the next. These shape changes indicate phase differences in the occurrence of the components. If components do occur out of phase with each other, single point latency and amplitude measurements may be suspect as measurements of manifestations of brain activity.

Switching Time Effect

The switching time effect described in the introduction did not occur in the way hypothesized. There were no differences in latency between the SAME and DIFF conditions. There are a few possible explanations for this. One is that the phase differences among N1 components could cause artifact in the single point latency measurements which make it difficult to measure or interpret any true changes in the time response of the evoked potential. Another is that variability in single responses could change as a result of change in stimulus frequency. This too could lead to average latency measurements based on artifact rather than changes in the response time of underlying neural mechanisms. A third explanation for the null switching time results of the present study is based on theoretical rather than measurement considerations. The N1 peak of the evoked potential is recognized as "exogeneous" , tied to stimulus characteristics rather than cognitive processing of the subject. The behavioral switching effects cited in the introduction may be more cognitive processing than stimulus or sensory processing. Ells and Gotts (1977) describe a series of four operations performed by a subject when asked to respond to a stimulus. The first two of these are , (1) forming a stimulus representation and (2) matching the stimulus representation to memory. It is possible that these operations occur at a higher cognitive level than that normally associated with N1 peak of the evoked response and that any advantages in processing conferred by a repetition in stimuli occurs in other, later peaks of the evoked potential. These later peaks are more commonly recognized as tied to higher order cognitive processes such as memory formations and comparisons. This explanation nullifies the neuronal switching hypothesis put forward in the literature review.

Although there were no quantitative differences between the SAME and DIFF conditions, there were some qualitative differences. Changes occurred in the SAME condition in the PSD of T3 as a function of ISI that did not occur in the PSD of T3 in the DIFF condition. T3 in the SAME condition showed a progressive decrease in a 3 Hz component with increasing ISI, and a progressive increase in a 10 Hz component with increasing ISI. This did not occur in the PSD of T3 DIFF. ISI has little effect on the PSD profile of T3 DIFF. T3 DIFF profiles from all three ISI's are very similar. This indicates that although there were no measurable single point N1 latency differences between the responses as a function of change in the auditory frequency of the stimuli, the timing and /or auditory processing components of the ERP may be influenced by changes in stimulus frequency.

Conclusion

The present study attempted to perform a comprehensive signal analysis on the evoked potential signal and to study the possible effects of stimulus frequency change on the latency of the evoked potential signal. The PSD profiles and the difference waves indicated a multi-component structure for the evoked potential. At least two of the frequency components revealed in the PSD were sensitive to sequence of stimuli and timing of stimuli. The difference waves between tones and between ISI's revealed shape differences between signals. These shape differences imply that the components that make up N1 respond on differing time scales (latencies) and/or to different degrees (amplitudes). These shifts in latency and amplitude among components complicate the interpretation of single point latency and amplitude measurements of the whole N1 signal. These single point measurements may not be simple, linear indications of time or strength changes in mechanisms underlying the response signals but may instead be average representations of latency and amplitude shifts among the components making up N1.

The stimulus presentation in the present study included a fourth tone that was not analyzed for the purposes of this investigation. This fourth tone may provide some additional information on sequence- and timing- sensitive components. Future work includes plans to analyze the response data from the fourth tone in the stimulus presentation. The presented signal analyses will also be used on any future evoked potential data in order to present a complete picture of the information contained within the signal. Because of the latency differences among components implied by the present signal analyses, Fourier phase analysis and latency measurements of difference waves will be important additions to any future signal analysis performed on evoked potential data. These particular analyses will help provide additional information on latency of N1 components.

These analyses expand the potential use of the evoked response as an indicator of brain activity. The greater the number of normal parameters (latencies, amplitudes, PSD profiles, potential energies, etc) that can be established for the response signal, the greater the use of the evoked response as a tool for studying both normal and abnormal brain functions.

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TABLE 1. MEAN AND SIGNIFICANT DIFFERENCE IN AMPLITUDE IN THE MEDIUM ISI.

COMPARISON		CONDITION	MEAN DIFFERENCE	SIGNIFICANT DIFFERENCE	ELECTRODE
T1 TO T2					
-14.43	-5.93	SAME	8.60	6.25(p<.05)	CZ
-12.48	-5.75	DIFF	6.73	6.25(p<.05)	CZ
-16.21	-7.28	SAME	8.93	6.25(p<.05)	FZ
-15.21	-7.59	DIFF	7.62	6.25(p<.05)	FZ
T1 TO T3					
-14.43	-5.80	SAME	8.63	6.25(p<.05)	CZ
-12.48	-6.04	DIFF	6.44	6.25(p<.05)	CZ
-16.21	-6.70	SAME	9.51	6.25(p<.05)	FZ
-15.21	-6.88	DIFF	8.33	6.25(p<.05)	FZ

TABLE 2. MEAN AND SIGNIFICANT DIFFERENCES IN AMPLITUDE IN THE LONG ISI.

COMPARISON		CONDITION	MEAN DIFFERENCE	SIGNIFICANT DIFFERENCE	ELECTRODE
T1 TO T2					
-13.50	-6.59	SAME	6.91	6.25(P<.05)	CZ
-13.26	-6.50	DIFF	6.76	6.25(P<.05)	CZ
-15.03	-8.30	SAME	6.73	6.25(P<.05)	FZ
-15.49	-7.58	DIFF	7.91	6.25(P<.05)	FZ
T1 TO T3					
-13.50	-6.27	SAME	7.23	6.25(P<.05)	CZ
-13.26	-6.67	DIFF	6.59	6.25(P<.05)	CZ
-15.03	-7.35	SAME	7.68	6.25(P<.05)	FZ
-15.49	-8.75	DIFF	6.74	6.25(P<.05)	FZ

TABLE 3. MEAN AND SIGNIFICANT DIFFERENCES IN AMPLITUDE IN THE SHORT ISI.

COMPARISON		CONDITION	MEAN DIFFERENCE	SIGNIFICANT DIFFERENCE	ELECTRODE
T1 TO T3					
-13.74	-6.39	SAME	7.35	6.25(P<.05)	CZ
-14.65	-8.23	DIFF	6.42	6.25(P<.05)	CZ
-16.20	-8.38	SAME	7.82	6.25(P<.05)	FZ
-16.31	-9.89	DIFF	6.42	6.25(P<.05)	FZ

TABLE 4. MEAN AND SIGNIFICANT DIFFERENCES IN ENERGY IN THE MEDIUM ISI.

COMPARISON		CONDITION	MEAN DIFFERENCE	SIGNIFICANT DIFFERENCE	ELECTRODE
T1 TO T2					
14663.84	2601.04	SAME	12062.80	11103(P<.05)	CZ
14754.31	3215.02	DIFF	11539.29	11103(P<.05)	CZ
18435.1	4666.52	SAME	13768.58	11103(P<.05)	FZ
12371.40	1112.61	DIFF	11258.79	11103(P<.05)	FZ
T1 TO T3					
14754.31	3410.84	DIFF	11343.47	11103(P<.05)	CZ
18435.10	3538.00	SAME	14897.10	11103(P<.05)	FZ

TABLE 5. MEAN AND SIGNIFICANT DIFFERENCES IN ENERGY IN THE LONG ISI.

COMPARISON		CONDITION	MEAN DIFFERENCE	SIGNIFICANT DIFFERENCE	ELECTRODE
T1 TO T2					
13406.15	2222.76	SAME	11183.39	11103(p<.05)	CZ
14707.60	2449.72	DIFF	12257.88	11103(p<.05)	CZ
15862.01	4637.04	SAME	11224.97	11103(p<.05)	FZ
20450.2	6187.11	DIFF	14263.09	11103(p<.05)	FZ
T1 TO T3					
15862.01	3538.10	SAME	12323.91	11103(p<.05)	FZ
20450.2	5382.30	DIFF	15067.90	11103(p<.05)	FZ

TABLE 6. MEAN AND SIGNIFICANT DIFFERENCES IN AMPLITUDE BETWEEN ISI'S FOR TONE 2.

COMPARISON		CONDITION	MEAN DIFFERENCE	SIGNIFICANT DIFFERENCE	ELECTRODE
SHORT TO MEDIUM					
-13.74	-5.93	SAME	7.81	6.25(p<.05)	CZ
-12.25	-5.75	DIFF	6.50	6.25(p<.05)	CZ
-16.20	-7.28	SAME	8.92	6.25(p<.05)	FZ

TABLE 7. MEAN AND SIGNIFICANT DIFFERENCES IN ENERGY BETWEEN ISI'S FOR TONE 2.

COMPARISON		CONDITION	MEAN DIFFERENCE	SIGNIFICANT DIFFERENCE	ELECTRODE
SHORT TO MEDIUM					
17030.44	2601.00	SAME	14429.44	11103(p<.05)	CZ
14404.2	3215.02	DIFF	11199.18	11103(p<.05)	CZ
SHORT TO LONG					
17030.44	2222.76	SAME	14807.68	11103(p<.05)	CZ
14404.2	2449.05	DIFF	11955.15	11103(p<.05)	CZ

TABLE 8. T1-T2 CHANGE: MEAN AND SIGNIFICANT DIFFERENCES IN AMPLITUDE BETWEEN ISI'S

COMPARISON		CONDITION	MEAN DIFFERENCE	SIGNIFICANT DIFFERENCE	ELECTRODE
SHORT TO MEDIUM					
1.76	8.5	SAME	6.74	6.25($p<.05$)	CZ
.47	6.73	DIFF	6.26	6.25($p<.05$)	CZ
2.39	8.93	SAME	6.54	6.25($p<.05$)	FZ
1.37	7.62	DIFF	6.25	6.25($p<.05$)	FZ
SHORT TO LONG					
1.37	7.91	DIFF	6.54	6.25($p<.05$)	FZ

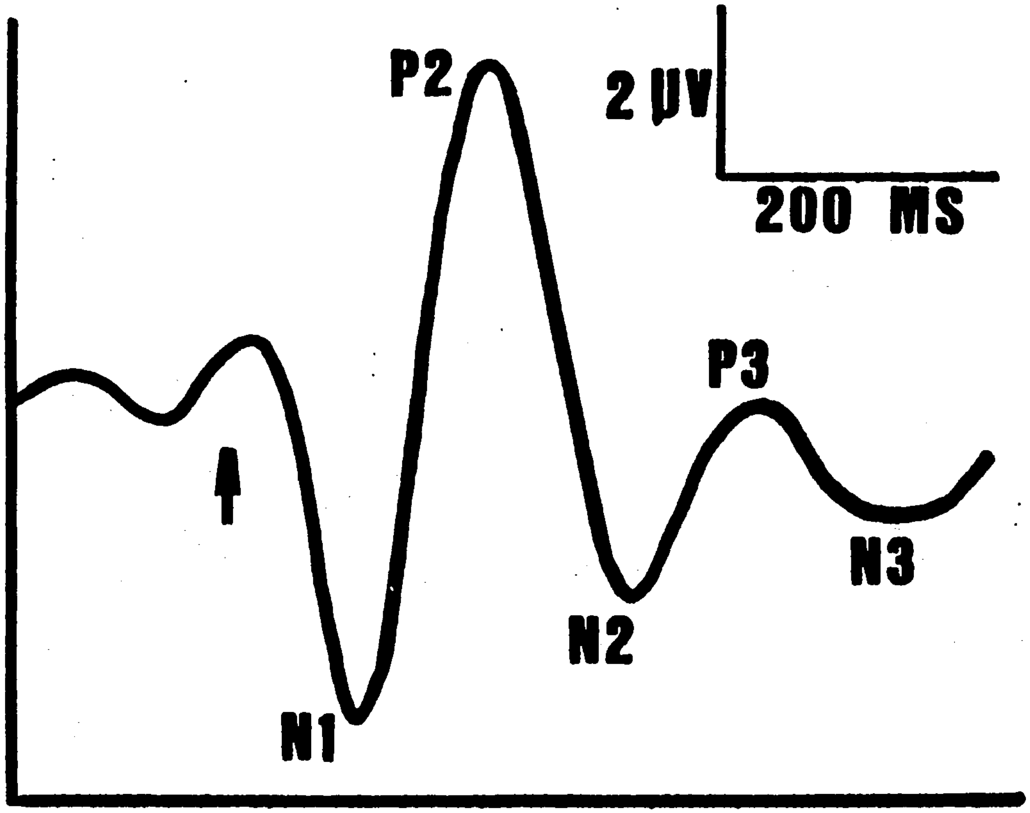

Figure 1. Example of an averaged evoked potential. Voltage is shown as a function of time. Arrow indicates stimulus.

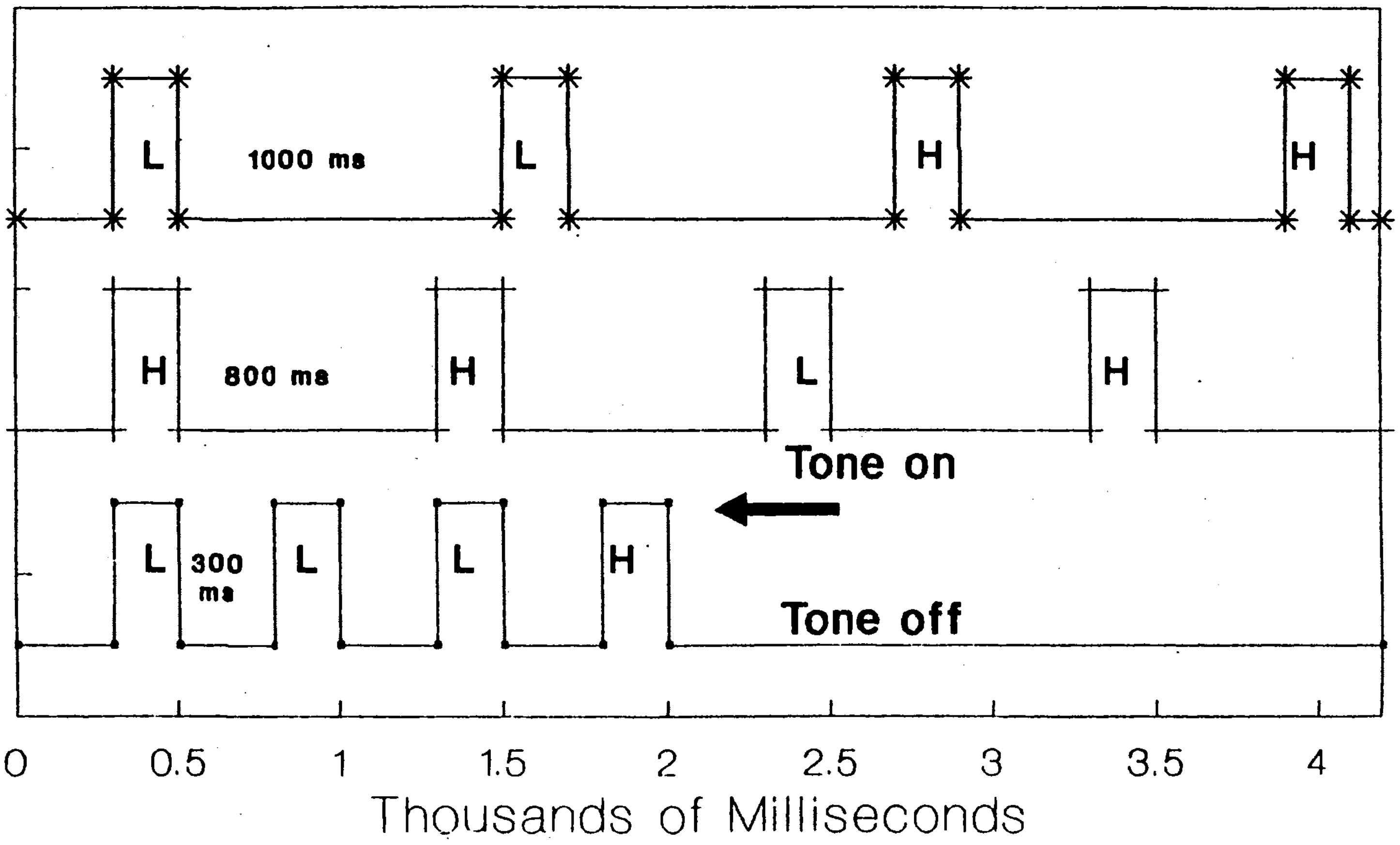

Figure 2. Examples of stimuli presentation in the present study. LLHH, HHLH, and LLLH are three of the eight frequency combinations that were used in the study.

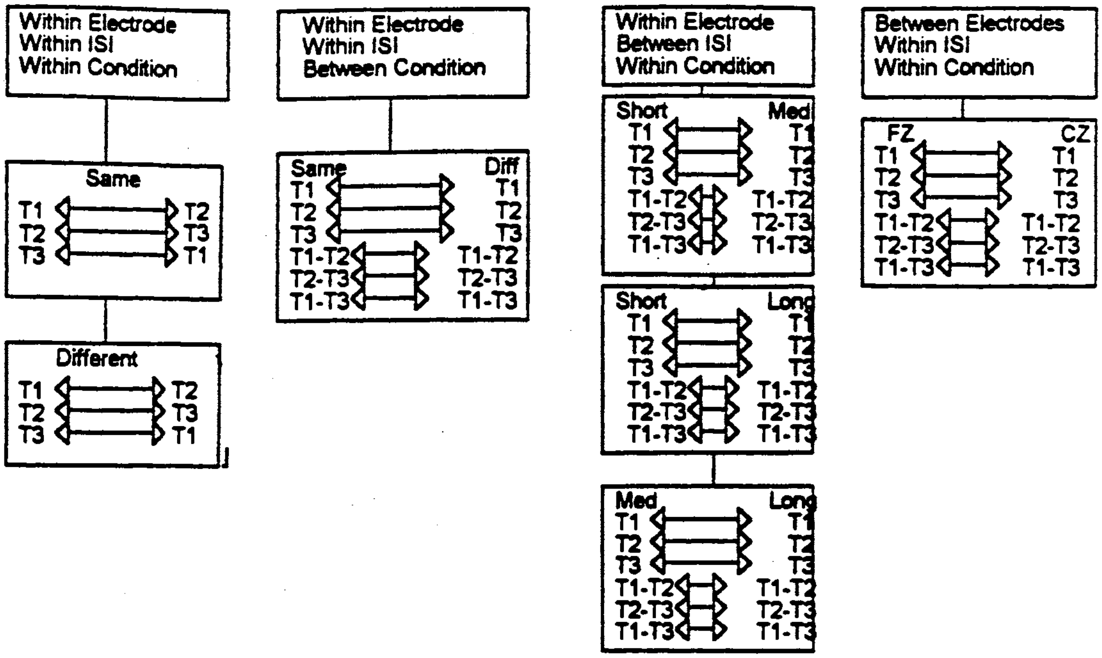

Figure 3. Within and between variable comparisons performed on the evoked potential data.

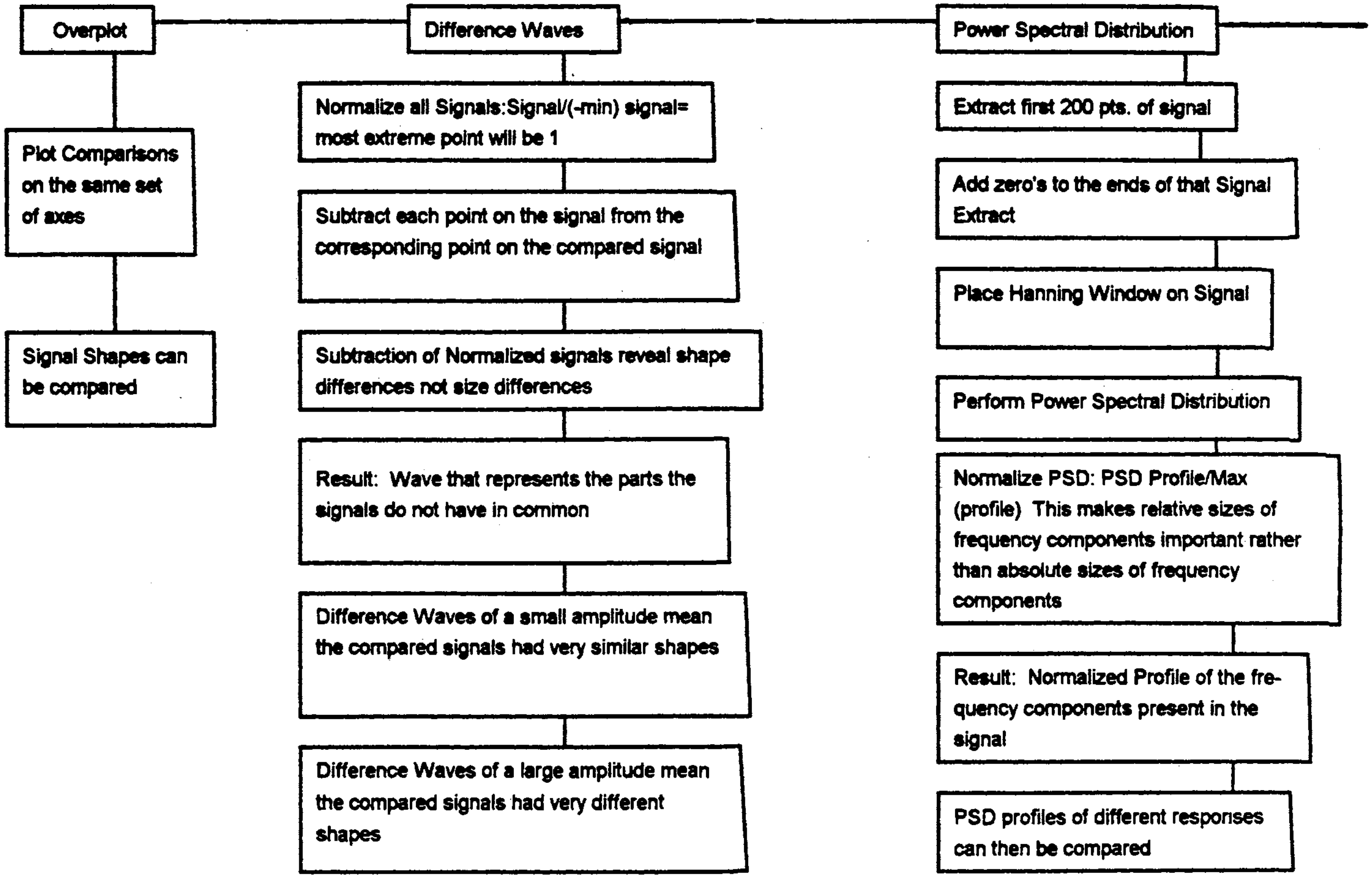

Figure 4. Qualitative signal analyses performed on comparisons made in Figure 3.

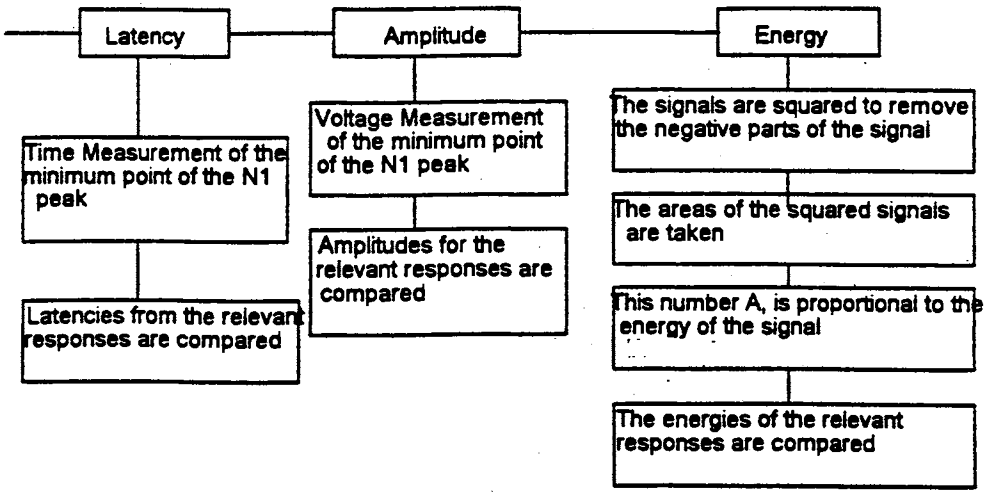

Figure 5. Quantitative signal analyses performed on comparisons done in Figure 3.

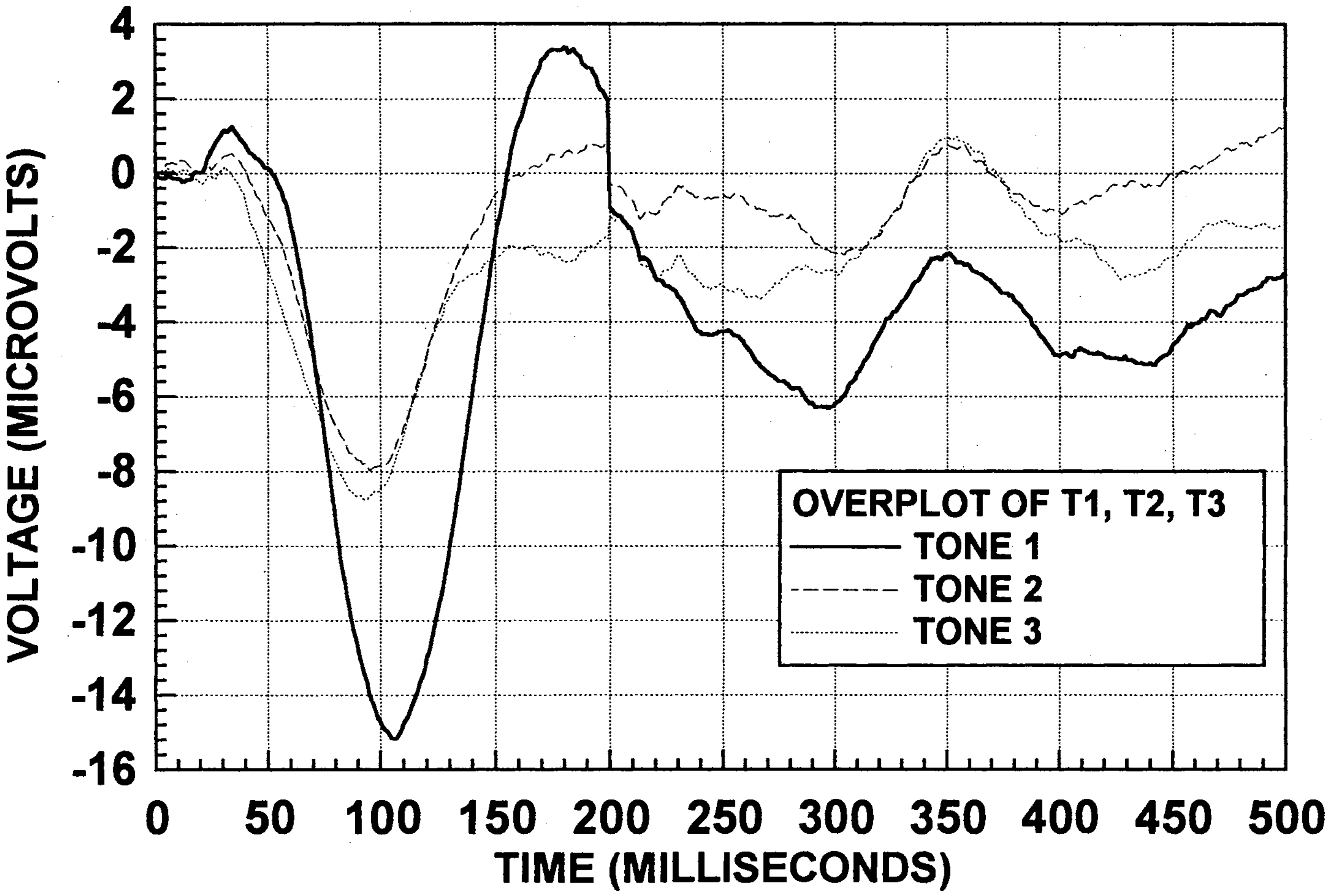

Figure 6. Overplot of the grand averages of the responses evoked by Tone 1, Tone 2, and Tone 3.

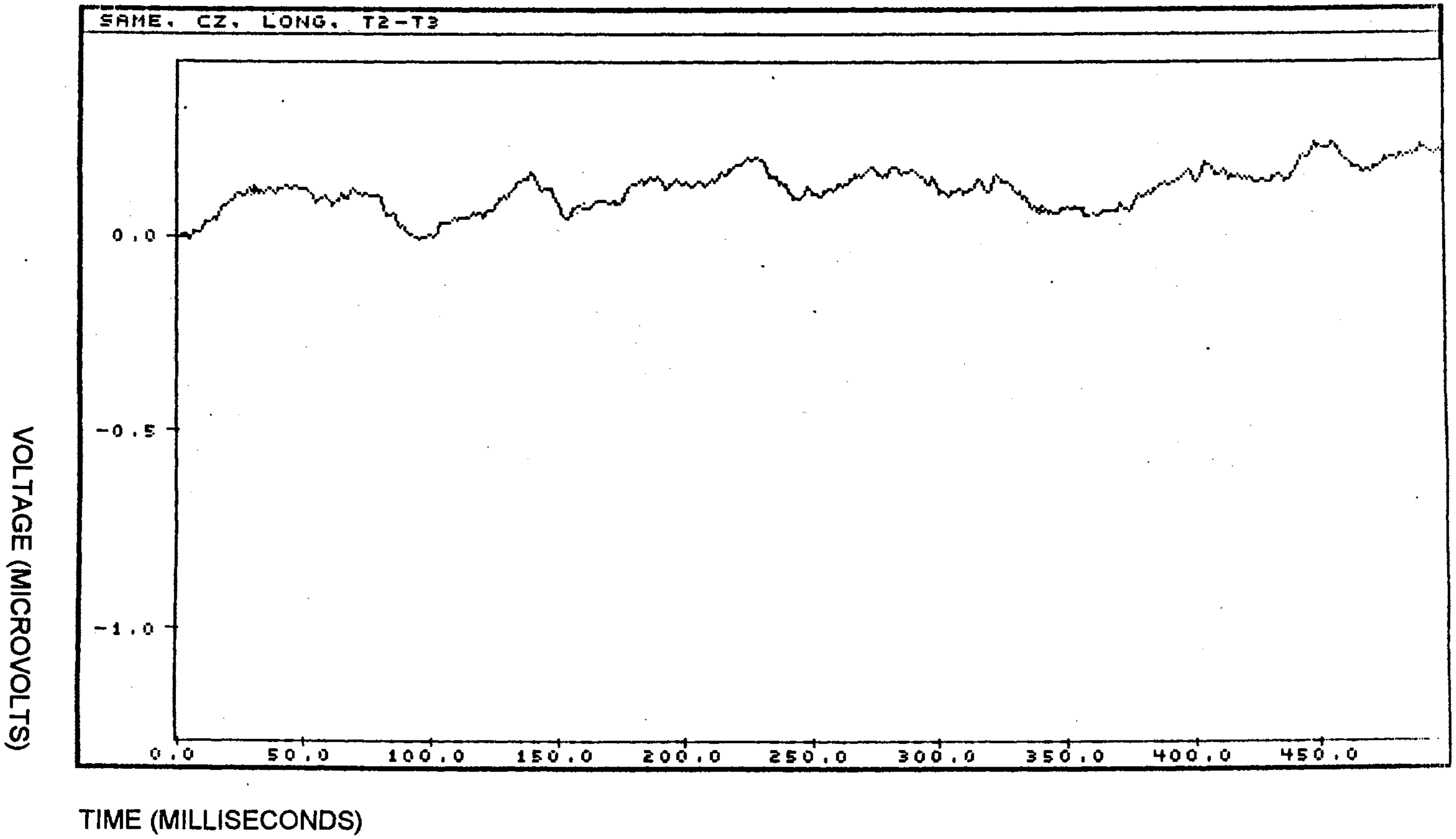

Figure 7 The flat difference wave established by a point-by-point subtraction of the normalized Tone 2response and the normalized Tone 3 response in the long ISI.

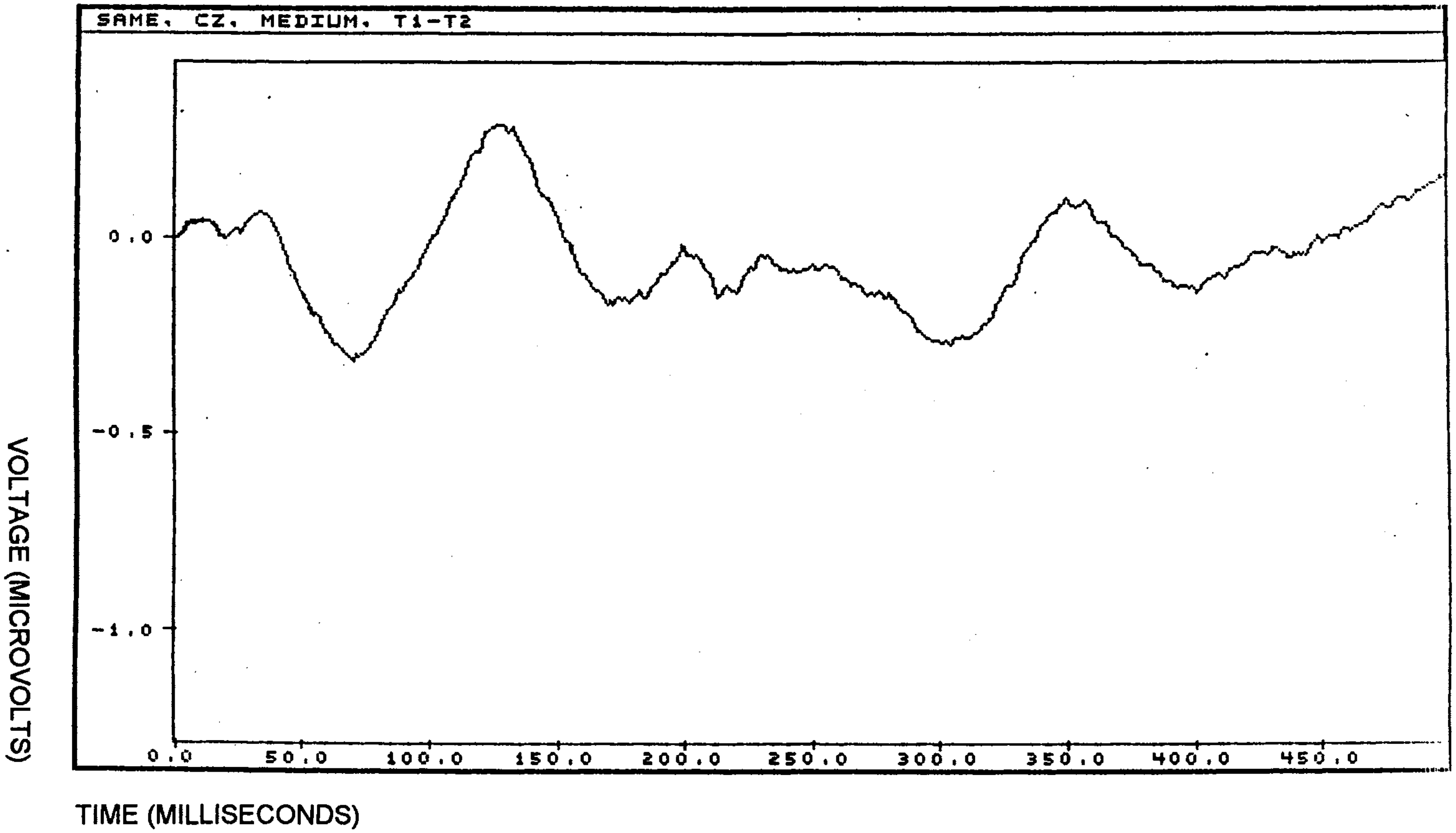

Figure 8. The difference wave established by a point-by-point subtraction of the normalized Tone 1 response and the normalized Tone 2 response in the medium ISI.

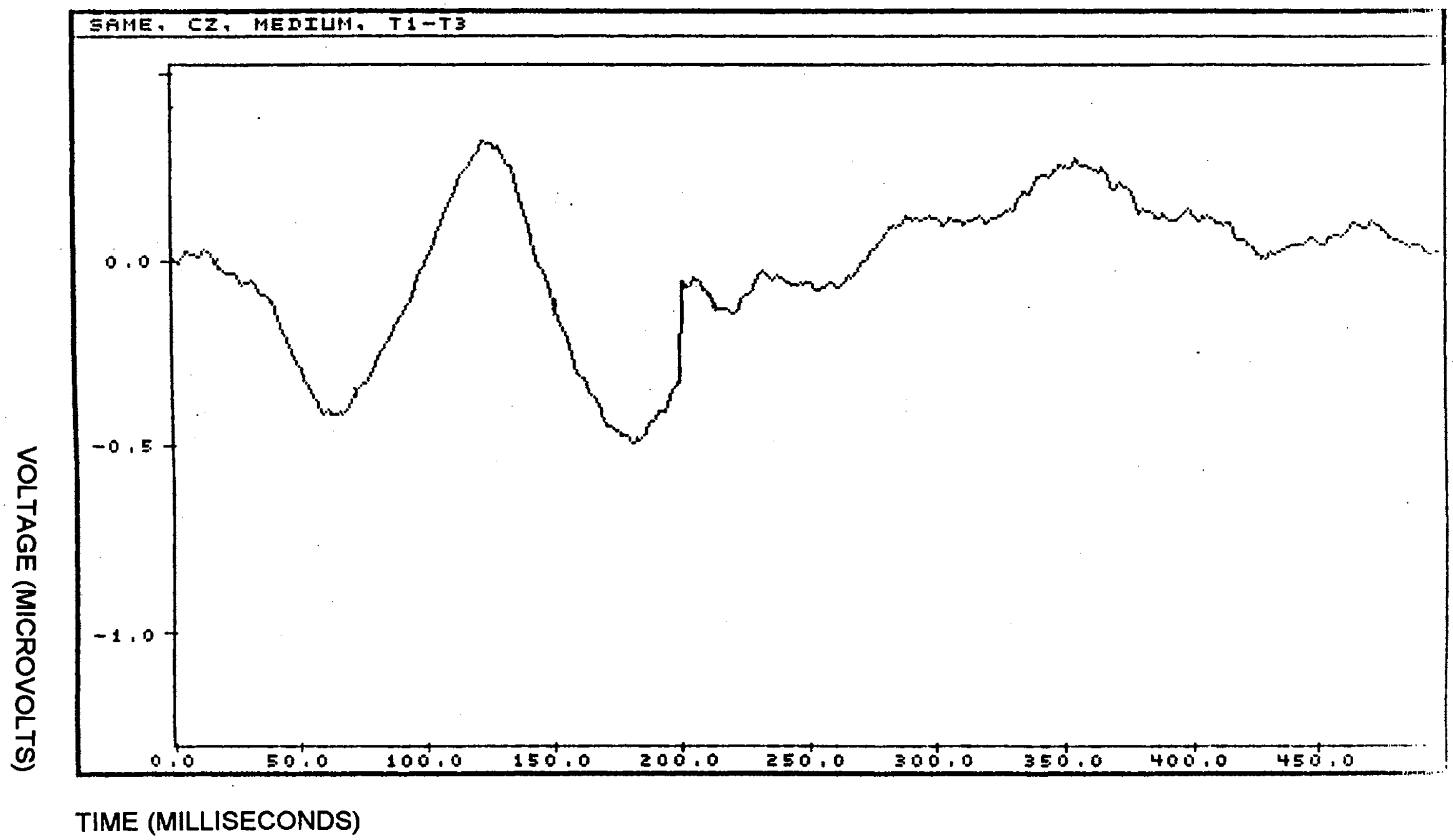

Figure 9. The difference wave established by a point-by-point subtraction of the normalized Tone 1 response and the normalized Tone 3 response in the medium ISI.

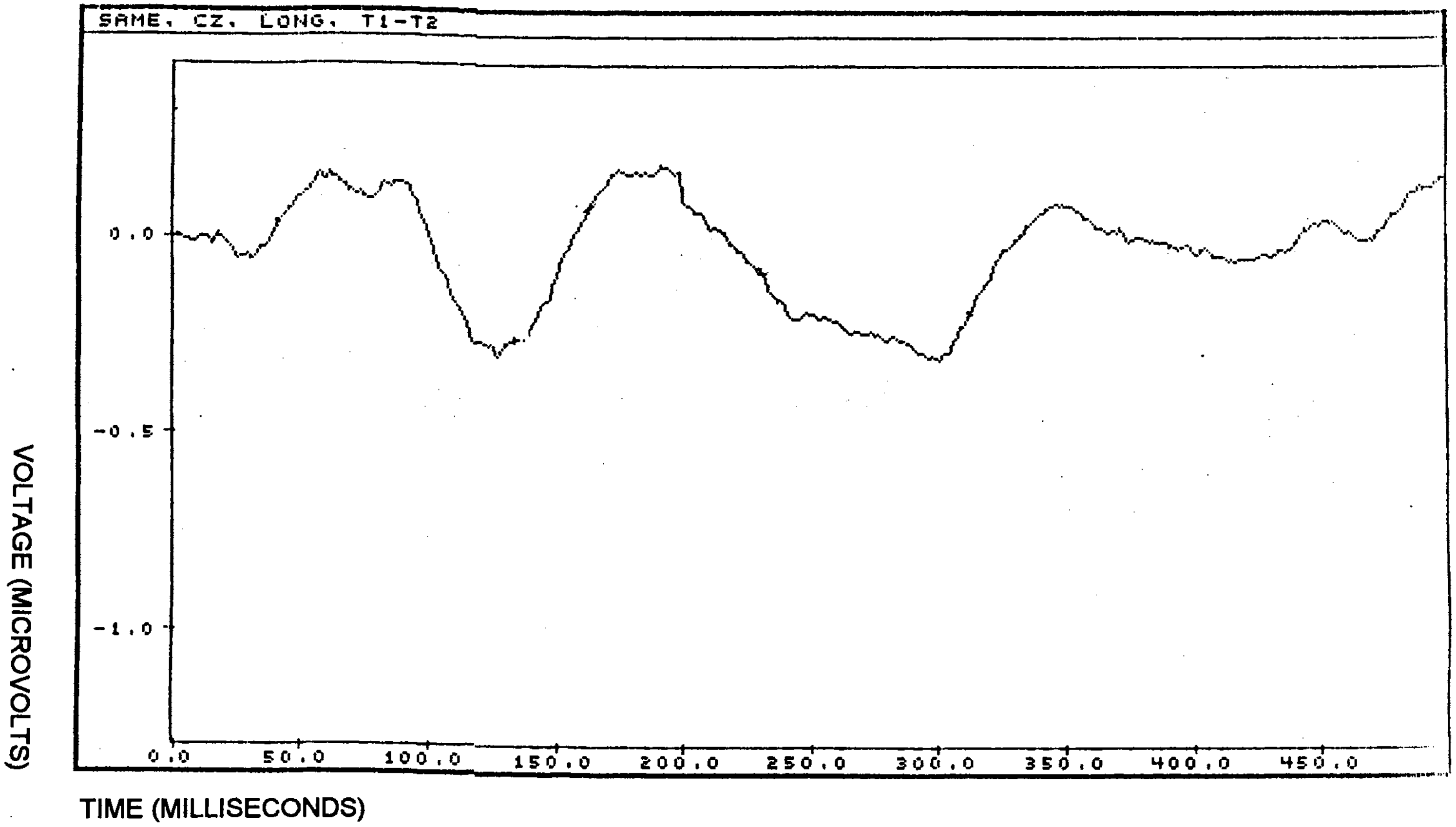

Figure 10. The difference wave established by a point-by-point subtraction of the normalized Tone 1 response and the normalized Tone 2 response in the long ISI.

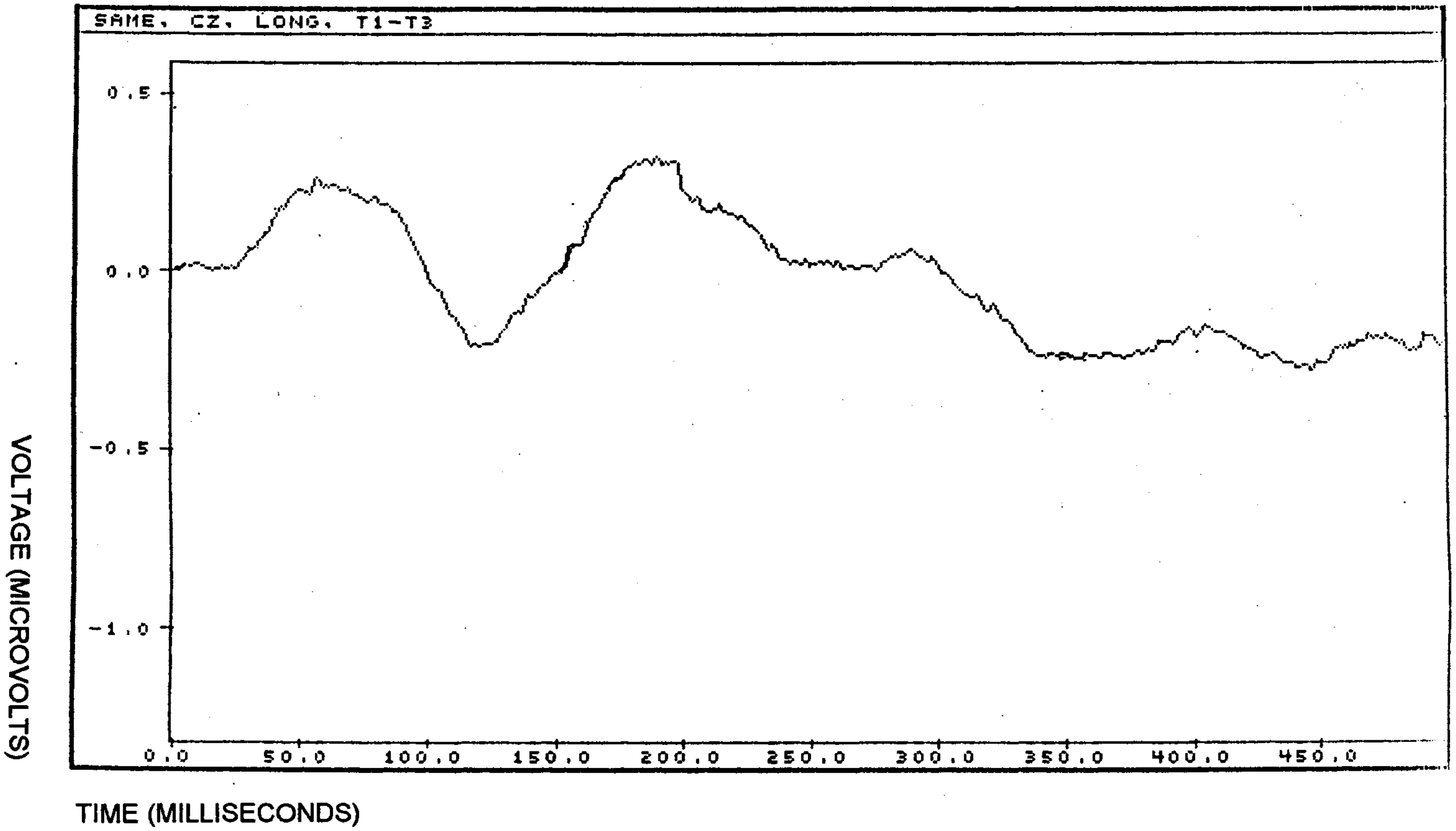

Figure 11. The difference wave established by a point-by-point subtraction of the normalized Tone 1 response and the normalized Tone 3 response in the long ISI.

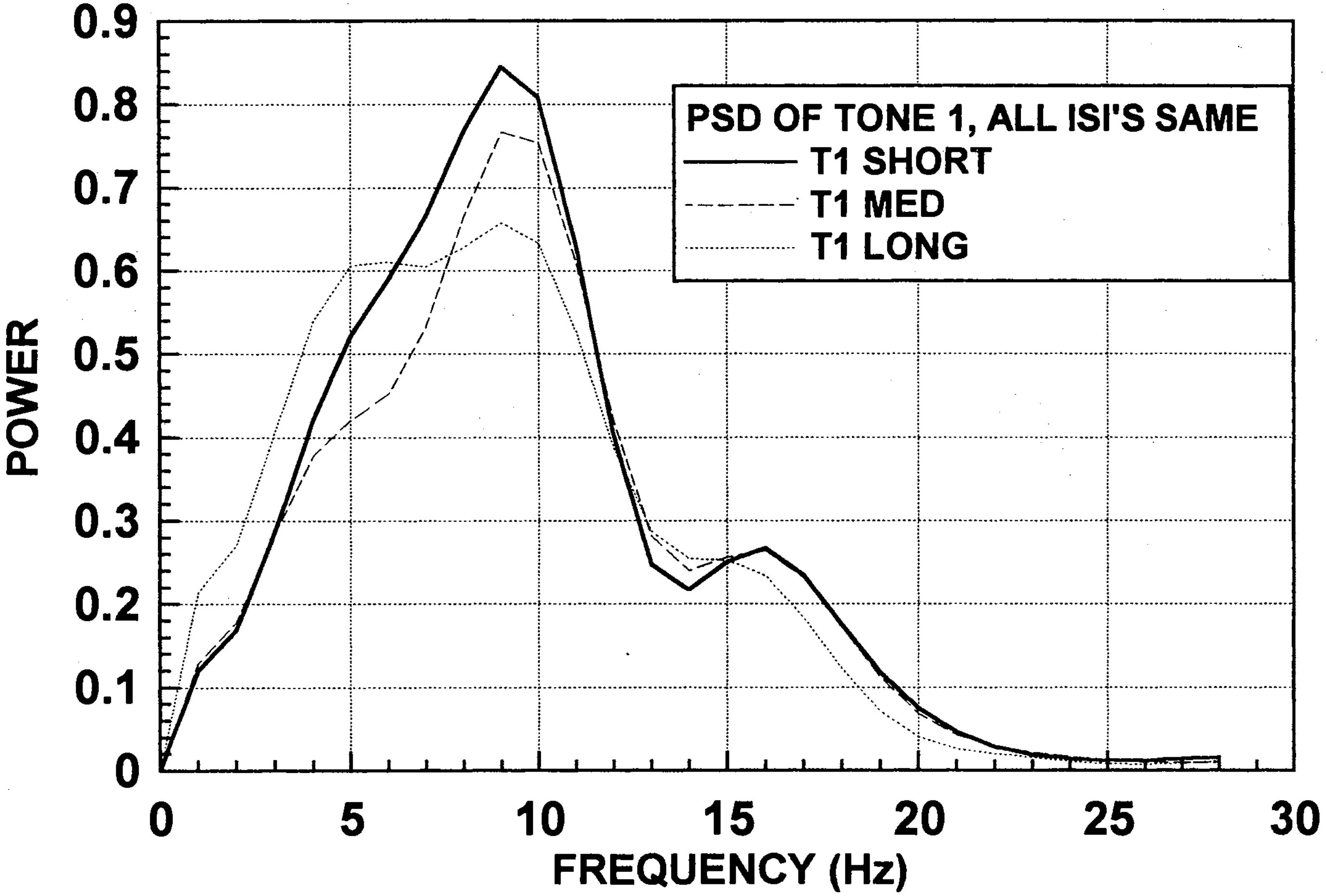

Figure 12. The frequency profile of all Tone 1 responses in the SAME condition. The profile was obtained by performing a power spectral density analysis on the signals.

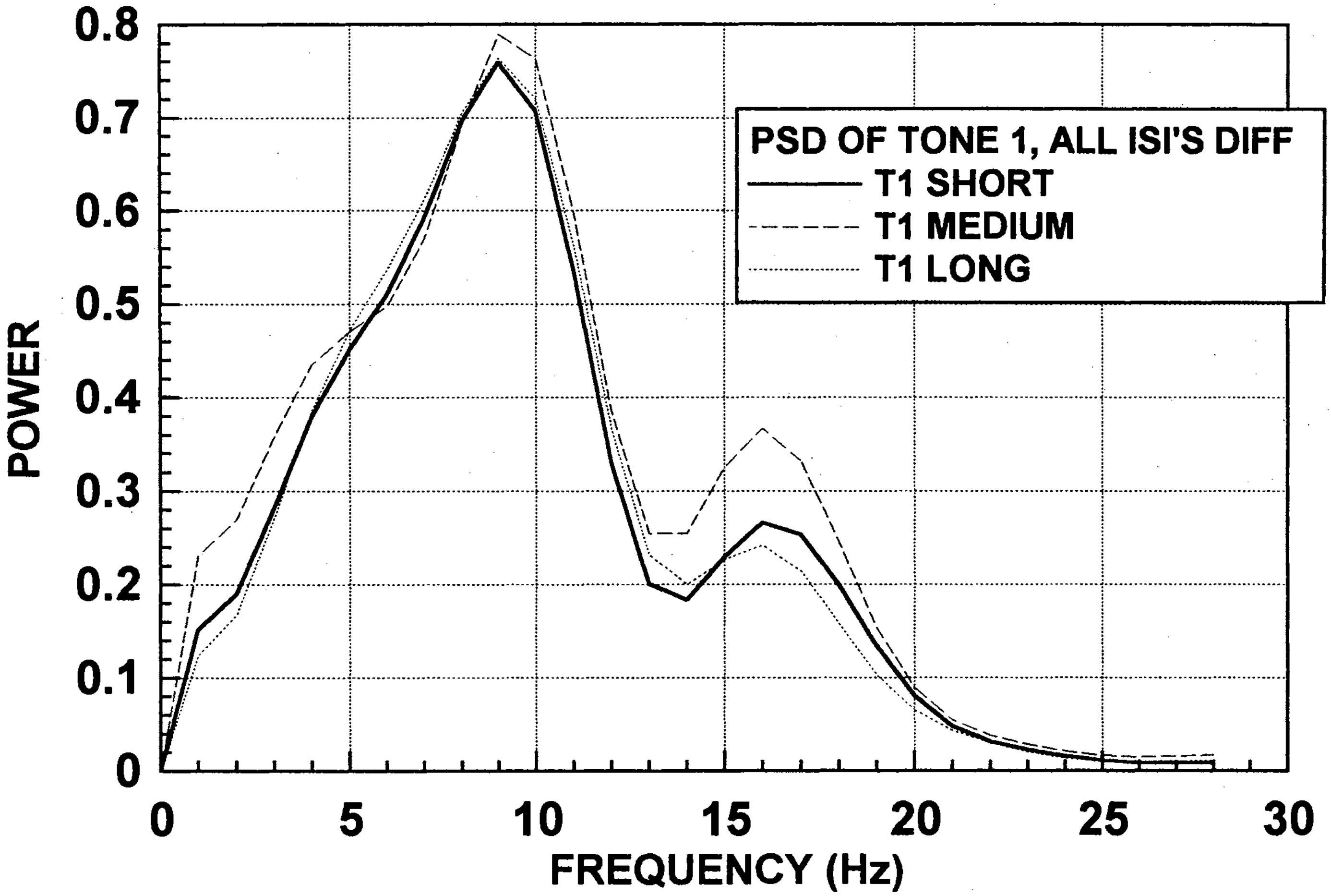

Figure 13. The frequency profile of all Tone 1 responses in the DIFF condition. The profile was obtained by performing a power spectral density analysis on the signals.

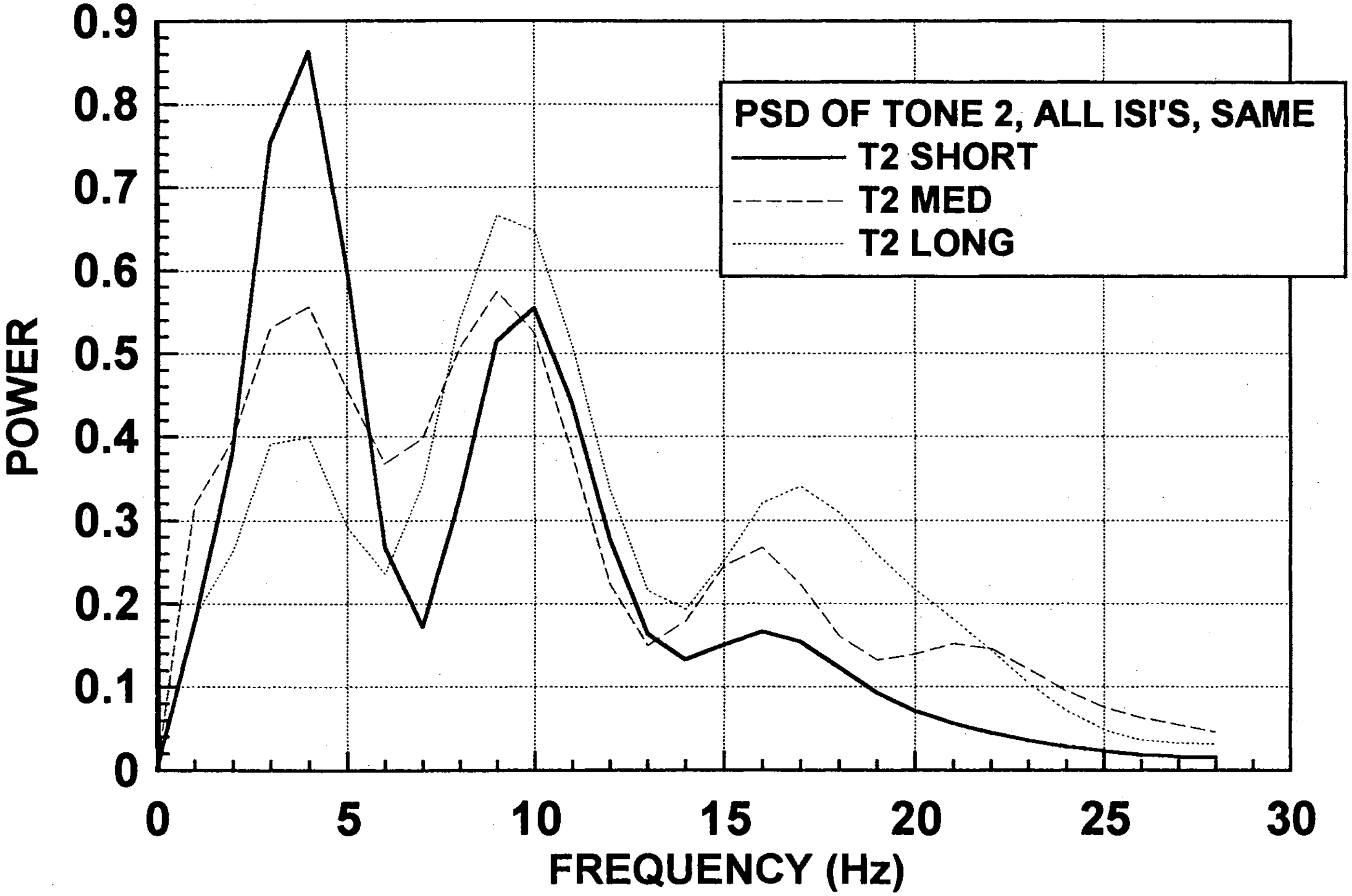

Figure 14. The frequency profile of all Tone 2 responses in the SAME condition. The profile was obtained by performing a power spectral density analysis on the signals.

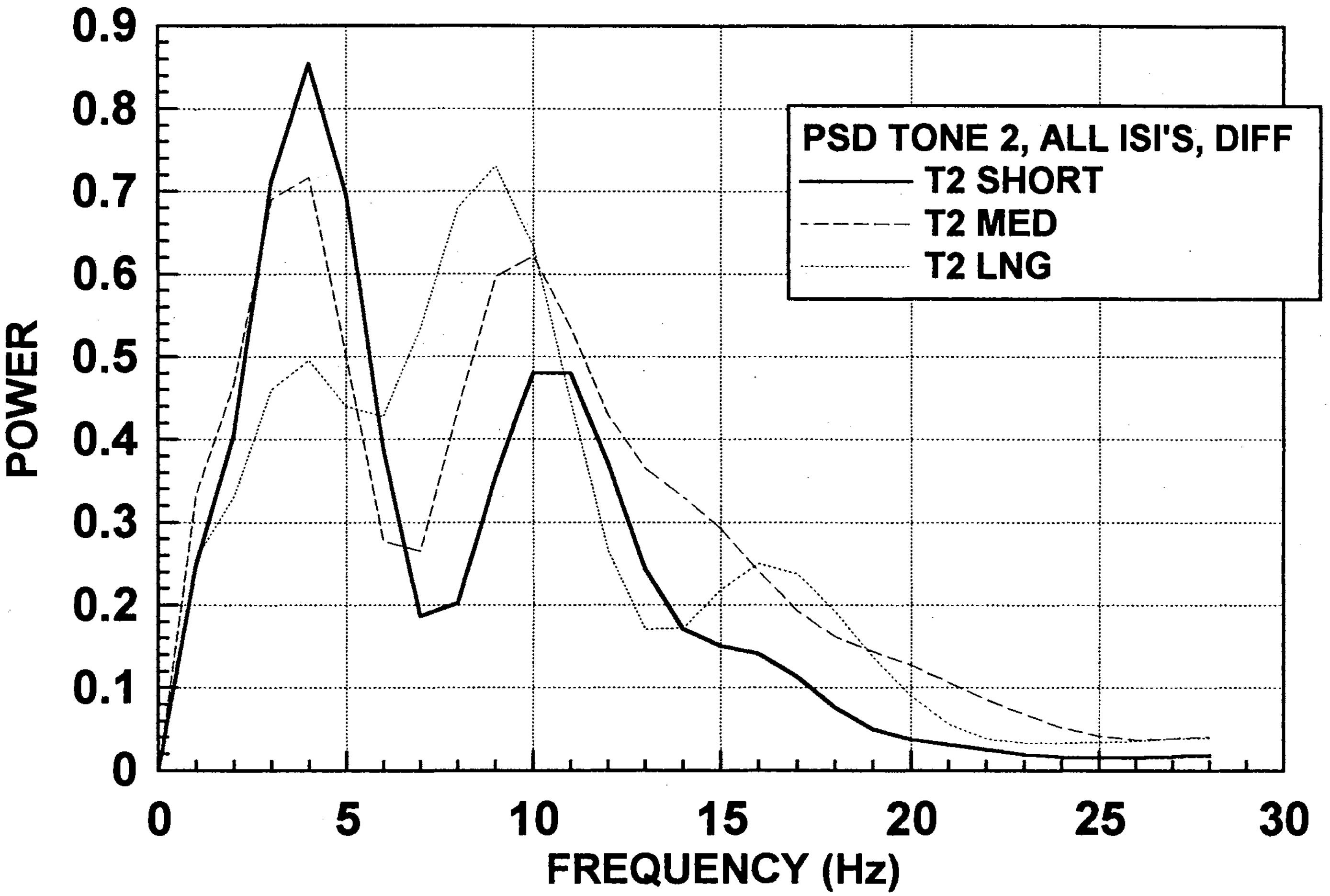

Figure 15. The frequency profile of all Tone 2 responses in the DIFF condition. The profile was obtained by performing a power spectral density analysis on the signals.

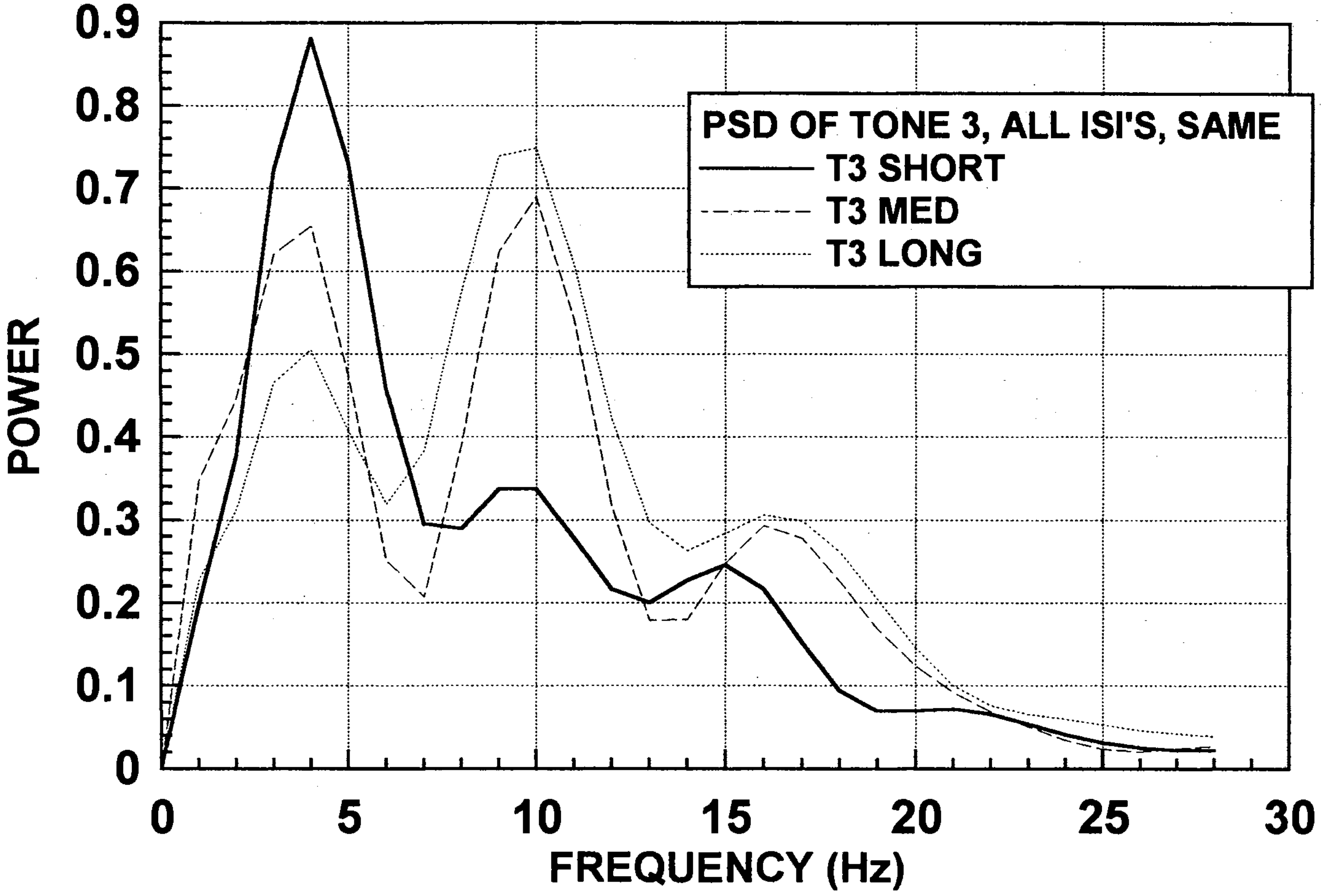

Figure 16. The frequency profile of all Tone 3 responses in the SAME condition. The profile was obtained by performing a power spectral density analysis on the signals.

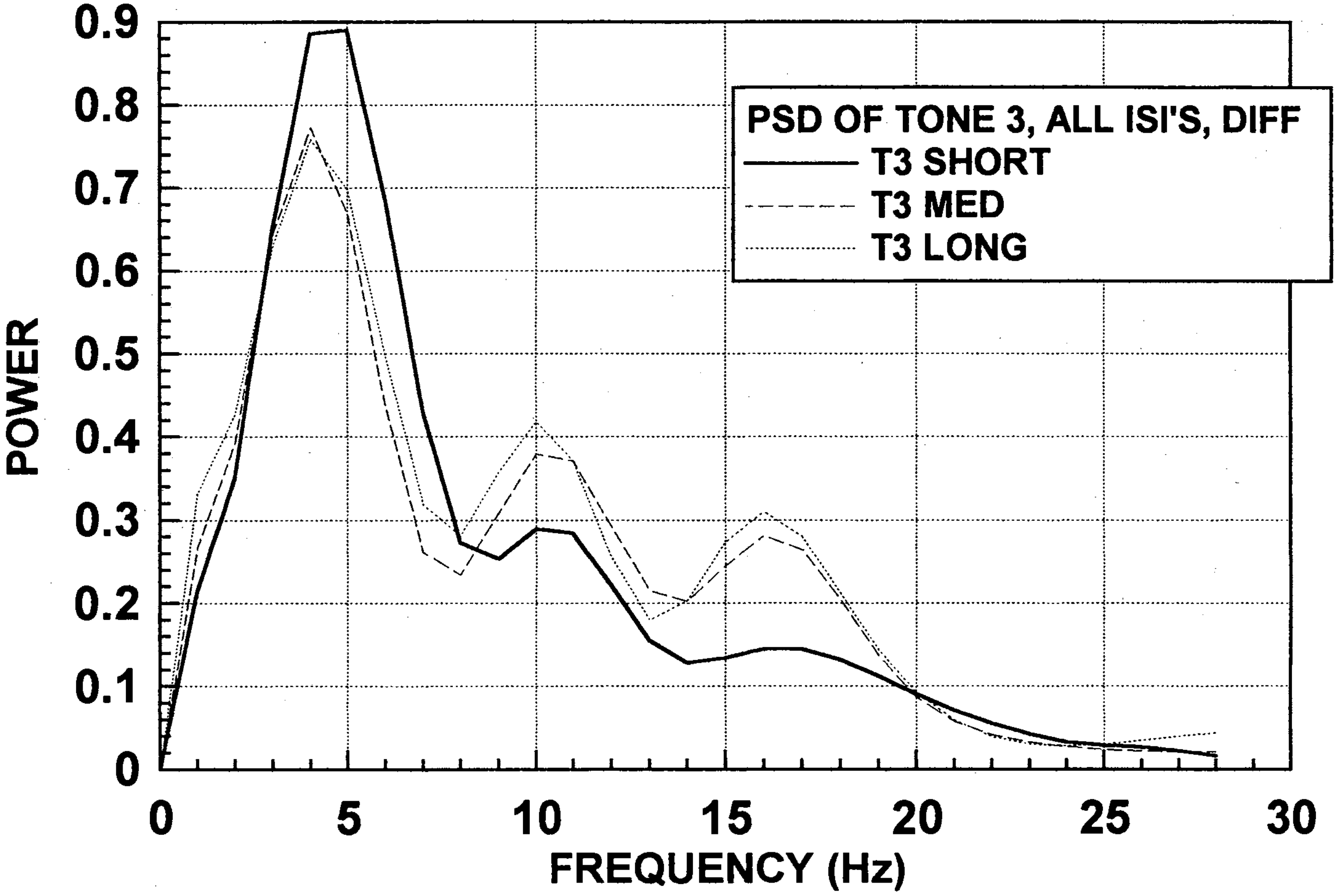

Figure 17. The frequency profile of all Tone 3 responses in the DIFF condition. The profile was obtained by performing a power spectral density analysis on the signals.

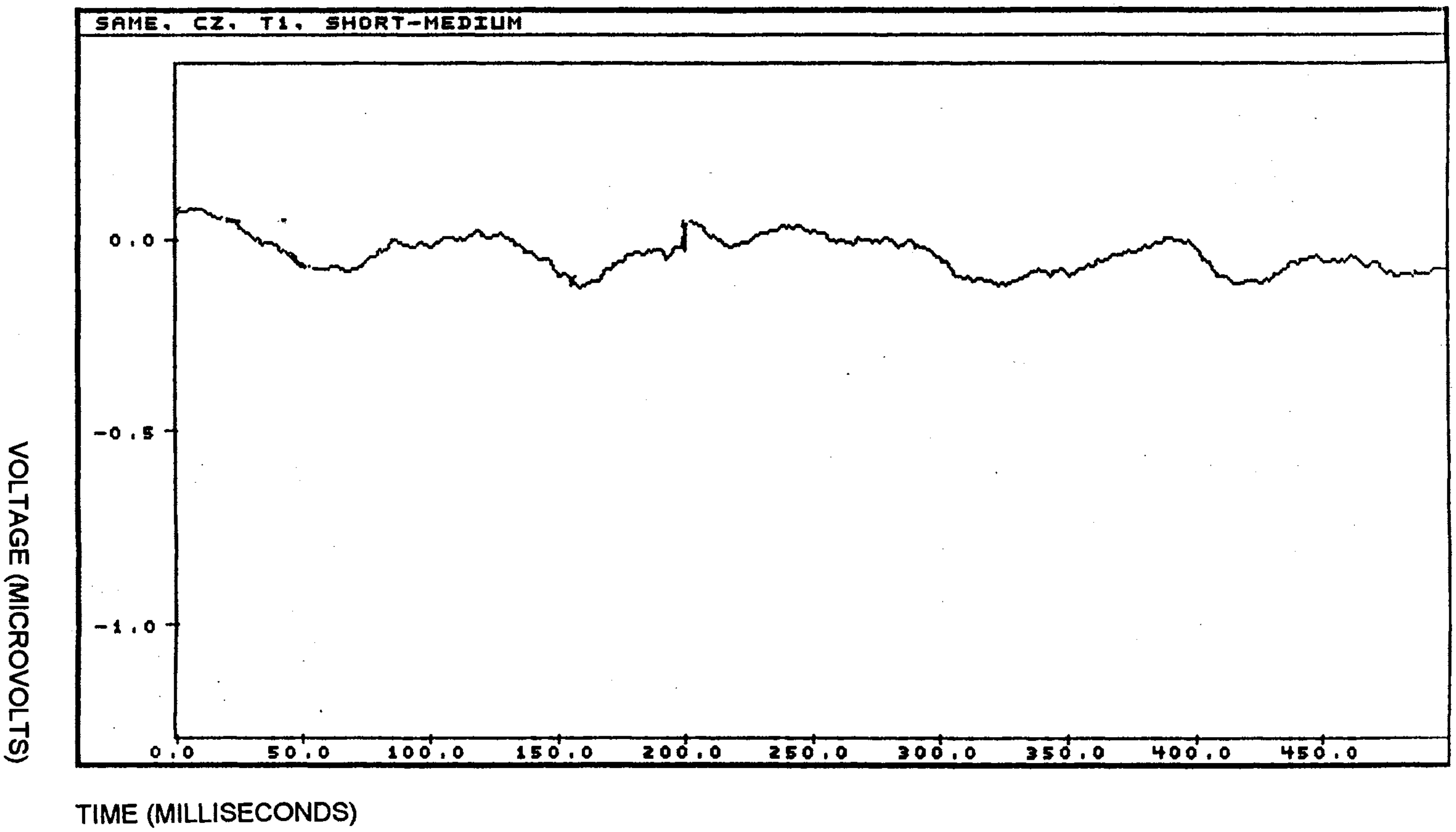

Figure 18. The flat difference wave established by a point-by-point subtraction of the normalized Tone 1 response in the short ISI and the normalized Tone 1 response in the medium ISI.

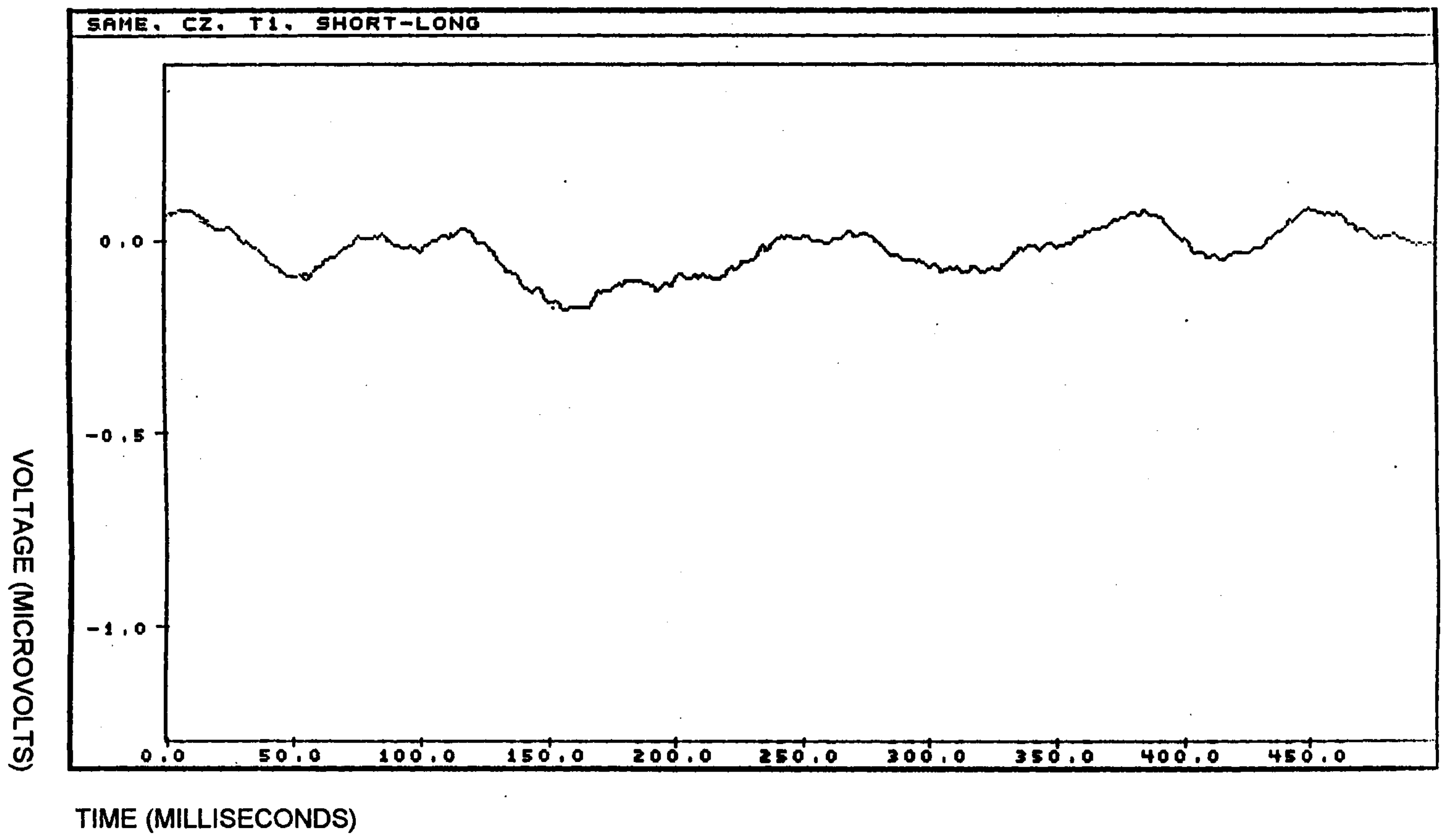

Figure 19. The flat difference wave established by a point-by-point subtraction of the normalized Tone 1 response in the short ISI and the normalized Tone 1 response in the long ISI.

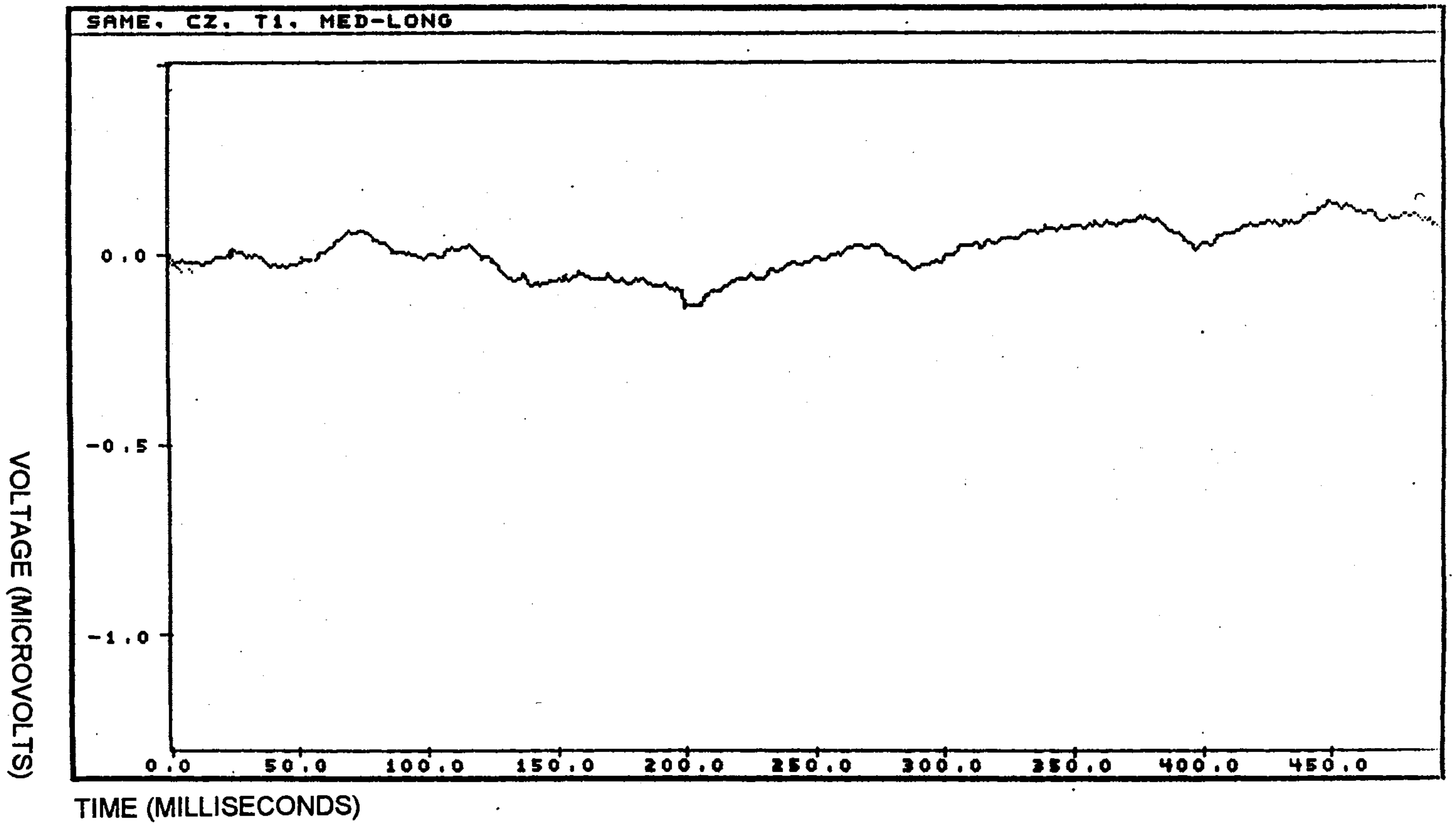

Figure 20. The flat difference wave established by a point-by-point subtraction of the normalized Tone 1 response in the medium ISI and the normalized Tone 1 response in the long ISI.

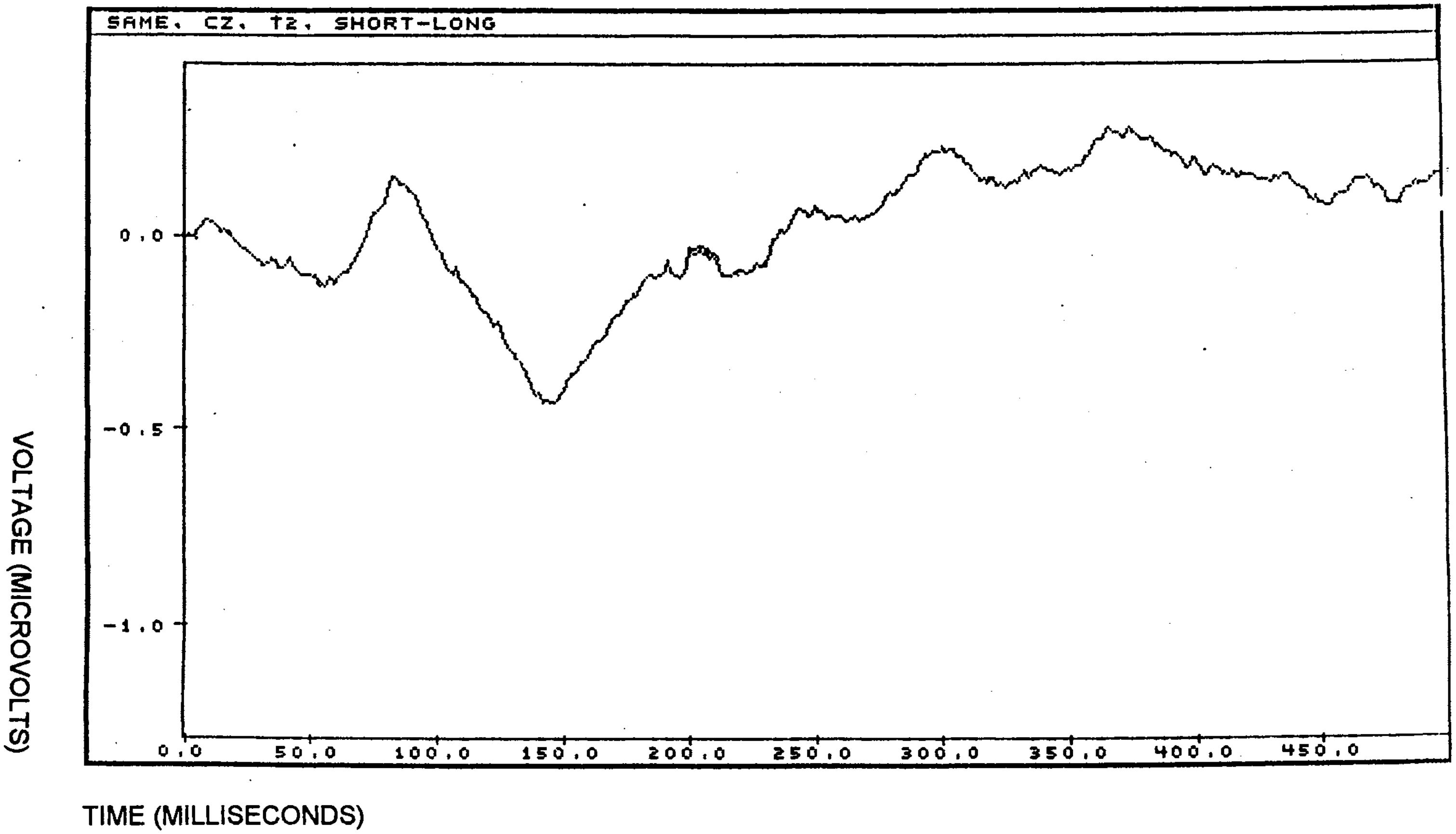

Figure 21. The difference wave established by a point-by-point subtraction of the normalized Tone 2 response in the short ISI and the normalized Tone 2 response in the long ISI.

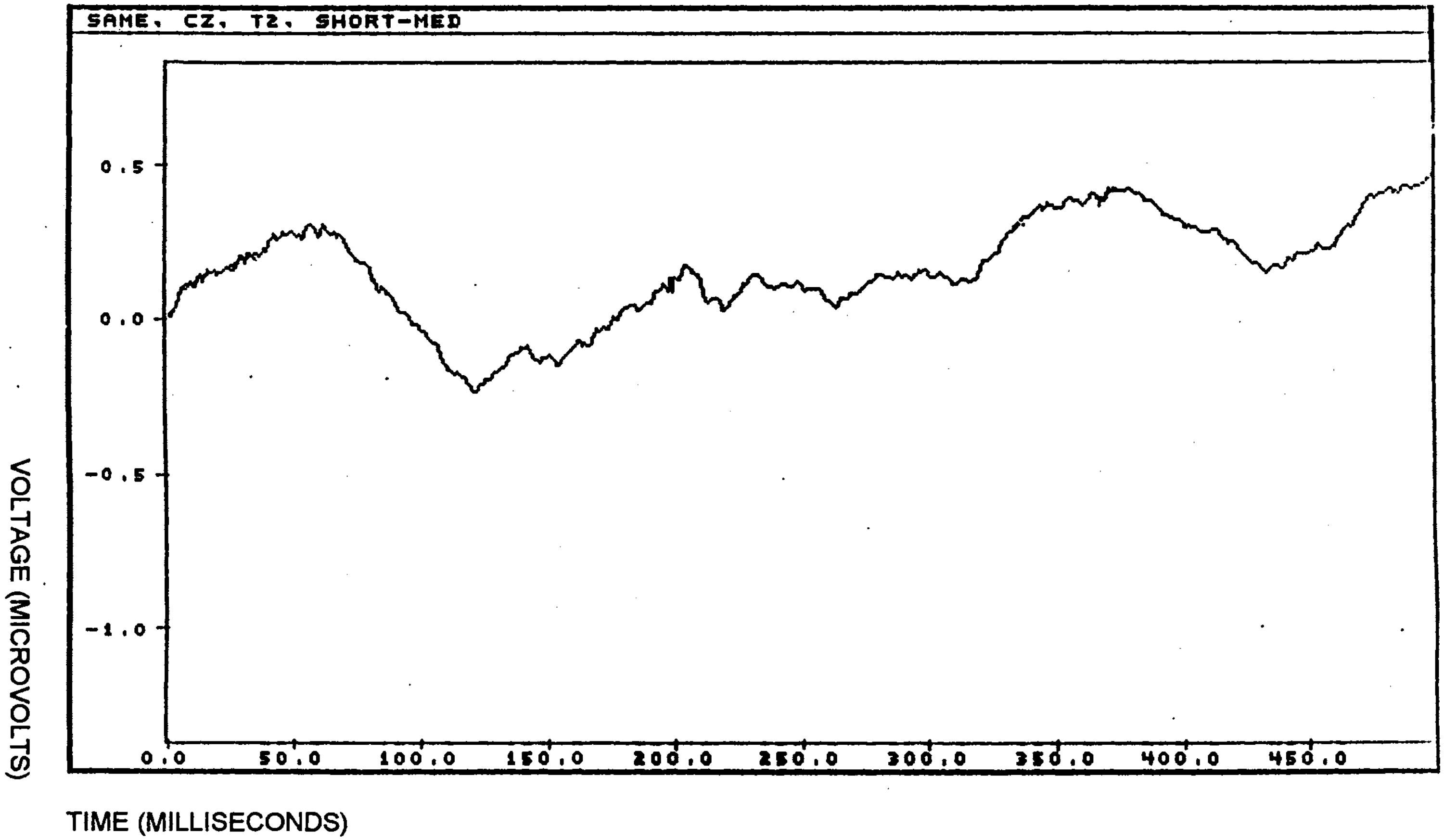

Figure 22. The difference wave established by a point-by-point subtraction of the normalized Tone 2 response in the short ISI and the normalized Tone 2 response in the medium ISI.

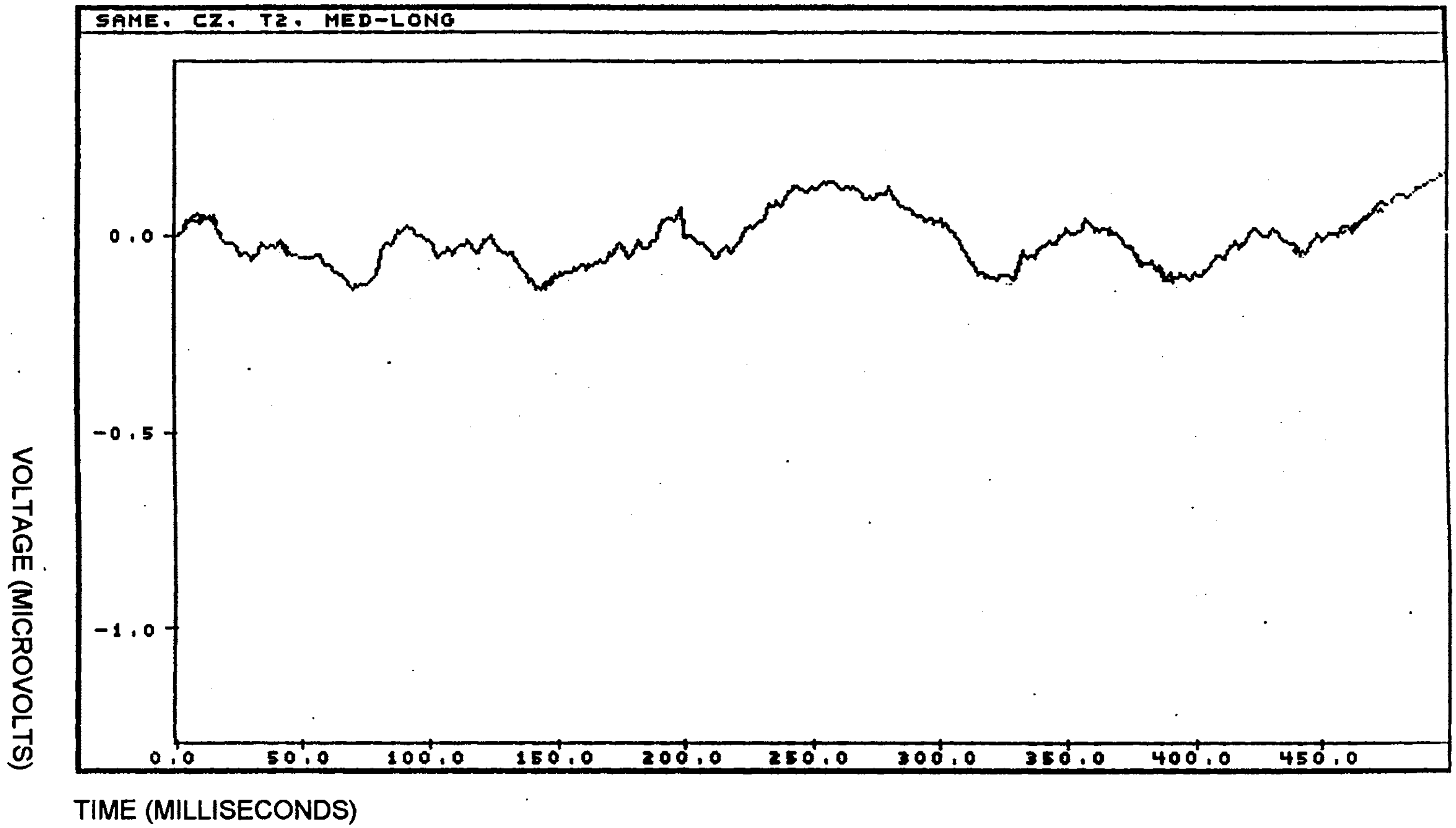

Figure 23. The difference wave established by point-by-point subtraction of the normalized Tone 2 response in the medium ISI and the normalized Tone 2 response in the long ISI.

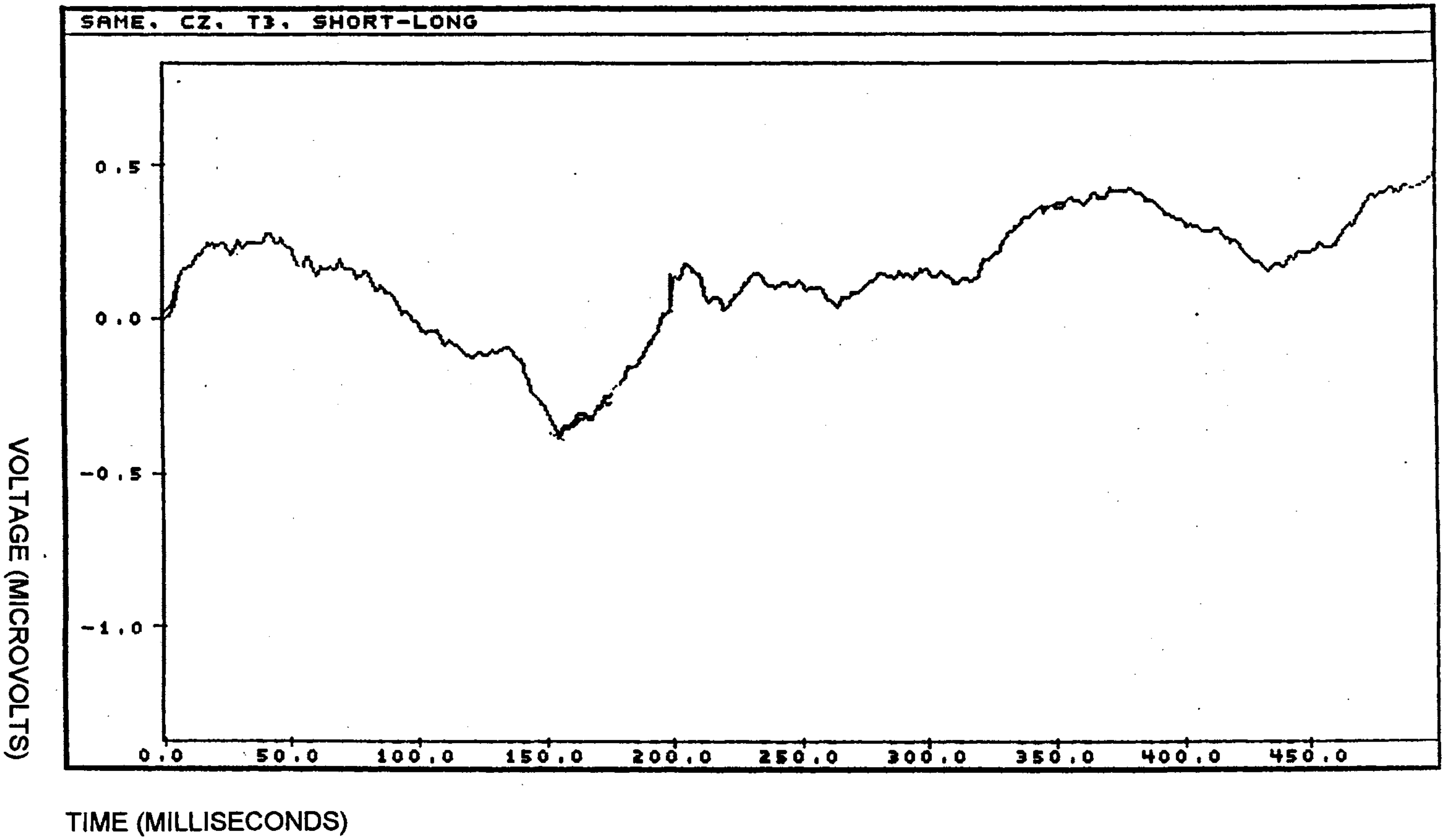

Figure 24. The difference wave established by a point-by-point subtraction of the normalized Tone 3 response in the short ISI and the normalized Tone 3 response in the long ISI.

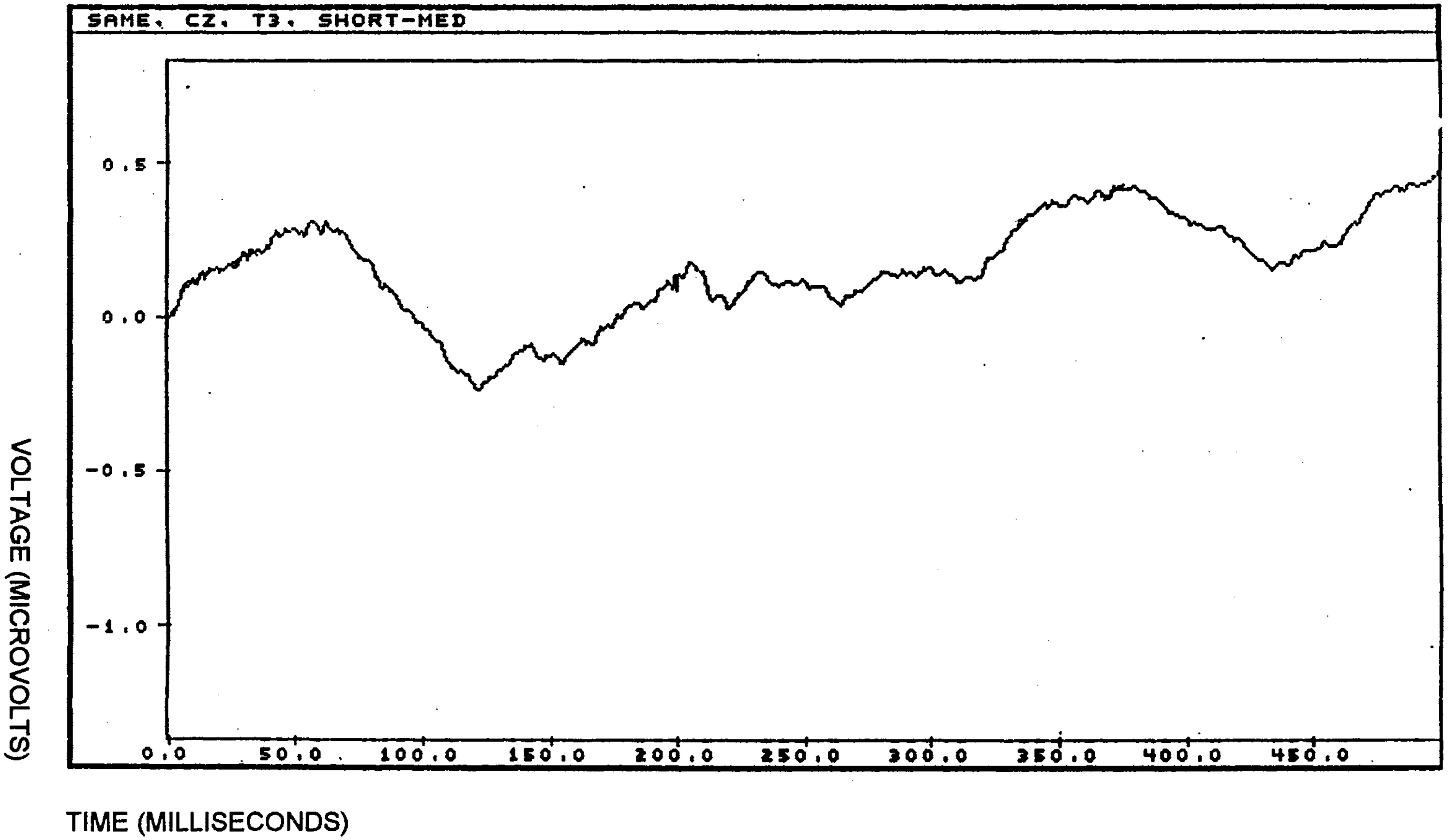

Figure 25. The difference wave established by a point-by-point subtraction of the normalized Tone 3 response in the short ISI and the normalized Tone 3 response in the medium ISI.

VITA

Elizabeth L. Whitaker

Candidate for the Degree of

Doctor of Philosophy

Thesis: AUDITORY EVENT-RELATED POTENTIALS AS A MEASURE OF SENSORY SWITCHING TIME

Major Field: Psychology

Biographical:

Personal Data: Twenty-eight year resident of Stillwater, Oklahoma. Married with one 6-year old daughter.

Education: Graduated from Perry High School, Perry, Oklahoma in May 1977; received Bachelor of Science degree in Psychology from Oklahoma State University, Stillwater, Oklahoma in December, 1985. Completed the requirements for the Master of Science degree with a major in Psychology at Oklahoma State University in December, 1989. Completed the requirements for the Doctor of Philosophy degree with a major in Psychology at Oklahoma State University in December, 1993.

Experience: Employed by the Oklahoma State University Department of Psychology as a graduate research and teaching assistant, 1988 to 1991.

Professional Memberships: American Psychological Society

OKLAHOMA STATE UNIVERSITY
INSTITUTIONAL REVIEW BOARD
FOR HUMAN SUBJECTS RESEARCH

Proposal Title: Auditory Event Related Potentials as a Measure of Sensory Switching Time

Principal Investigator: D. Thomas/E. Whitaker

Date: 2-14-92 IRB # AS-92-031

This application has been reviewed by the IRB and

Processed as: Exempt [ ] Expedite [X] Full Board Review [ ]

Renewal or Continuation [ ]

Approval Status Recommended by Reviewer(s):

Approved [X] Deferred for Revision [ ]

Approved with Provision [ ] Disapproved [ ]

Approval status subject to review by full Institutional Review Board at next meeting, 2nd and 4th Thursday of each month.

Comments, Modifications/Conditions for Approval or Reason for Deferral or Disapproval:

The Informed Consent Form was taken from a previous related study and needs to be updated. That is, the consent form should show the title of the current study, the name of the co-investigator (Elizabeth Whitaker) who will be collecting the data, and LeAnn Prater as the contact person within University Research Services, rather than Terry Macuila.

Signature: Marcia L. Tilley Date: 2-25-92
Chair of Institutional Review Board