Comparison of behavioral discrimination, MMN and P300 to speech and non-speech stimuli

Joanna Dee Webster
University of Tennessee

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I am submitting herewith a thesis written by Joanna Dee Webster entitled "Comparison of behavioral discrimination, MMN and P300 to speech and non-speech stimuli." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Arts, with a major in Audiology.

Ashley W. Harkrider, Major Professor

We have read this thesis and recommend its acceptance:

Accepted for the Council:
Carolyn R. Hodges
Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)
To the Graduate Council:

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[Signature]
Ashley W. Harkrider, Major Professor

We have read this thesis and recommend its acceptance:

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Mark E. Hedrick

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Acceptance for the Council:

[Signature]
Vice Provost and Dean of Graduate Studies
COMPARISON OF BEHAVIORAL DISCRIMINATION, MMN AND P300 TO SPEECH AND NON-SPEECH STIMULI

A Thesis
Presented for the Master of Arts Degree at the University of Tennessee, Knoxville

Joanna Dee Webster
May 2002
I could not have made it through the process of writing this thesis without the support of many people. To all of those who encouraged me, I extend my gratitude for all they have contributed.

I owe eternal gratitude to my parents, Joe and Diana Webster, for all they have offered me in life. Without their unconditional love and encouragement I could never achieve my goals.

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I am thankful for the assistance of Dr. Mark Hedrick who aided in the production of the stimuli used in this project and provided me with the use of his lab. Your professional advise and countless contributions to this project are appreciated.

I am grateful for the guidance of Dr. James Thelin who has ensured that I was “being challenged” from the first day of my graduate career. Not only have you encouraged and challenged me throughout my study, but you also made me laugh.

To Greg Tampas, your patience, love and support, along with the occasional push, lead me successfully through this challenge. You are the best person I know and my best friend.
Abstract

This study examined the relation of central auditory processes and perception abilities to speech and non-speech stimuli. Behavioral responses and auditory evoked potentials (MMN and P300) of ten native English speaking males/females were evaluated to consonant-vowel speech (two within-category stimuli) and non-speech (two frequency glides whose frequencies matched the formant transitions of the consonant-vowel stimuli) synthetically-generated contrasts. The stimuli were presented monaurally to the right ear of all listeners. Listeners exhibited the best discrimination to the non-speech in same/different and oddball behavioral discrimination procedures. MMN responses were present in all subjects, without regard to stimulus type. P300s were elicited in nine of ten subject to the non-speech contrast, and in four of ten to the speech contrast. These results suggest that the two types of stimuli were processed differently in behavioral responses and P300 but not in the MMN responses. The enhanced discrimination of the frequency glide (non-speech) stimuli versus the CV (speech) stimuli of analogous acoustical content support the idea that the processing of speech is mediated differently than non-speech at higher levels in the auditory system.
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CHAPTER 1

Introduction

Compared to other acoustic signals, speech is a complex and dynamic phenomenon that varies in the frequency, amplitude, and time domains. It has been proposed that speech is perceived differently than other acoustic stimuli. Consequently, the relationship between a listener’s perception of acoustic signals and the neurophysiological responses to those signals are of great importance in studying and understanding the underlying biological processes responsible for the perception of sounds. Thus, understanding speech perception requires knowledge of how various types of acoustic stimuli are represented in the central auditory system and how they are transformed into meaningful signals. Auditory research has produced a vast understanding of peripheral auditory structure, function and the transduction of acoustic signals into neural codes. However, the complexity of central auditory processes, pathways and perception are much less understood.

The literature on speech perception debates the distinction between various levels of processing of speech signals (e.g., acoustic, phonetic, semantic). There is a large body of literature that examines an acoustic versus phonetic processing of speech. This processing can be evaluated through a combination of behavioral procedures that may include labeling and/or discrimination procedures, and also via electrophysiologic measures. The latter allows the evaluator a direct, objective measurement of speech detection. By measuring evoked potentials, such as the mismatch negativity (MMN) and P300, along with behavioral responses to auditory stimuli, a relation of central auditory processes and perception ability can be established.
This study examined the relationship between auditory evoked potentials (AEPs) and psychophysical responses to linguistic and non-linguistic stimuli. The responses were used to detect the presence, if any, of differential processing to non-speech (frequency glides) and speech (consonant-vowel) stimuli.
CHAPTER II

Review of Literature

Processing Levels of Speech

Dalebout & Stack (1999) proposed three processing levels in the perception of speech. First, there is an auditory level of processing in which an acoustic waveform is converted into a neural code. Second, the phonetic/phonemic level is responsible for the narrowly tuned sensitivity to phonemic contrasts that exist in response to native languages of adults and the broad sensitivity of infants to phonetic contrasts of any language. Lastly, there exists a higher-order linguistic processing level wherein lexical, syntactic and semantic knowledge mediates perception. MMN, P300, and behavioral studies may measure these various levels of processing, respectively. The phonetic/phonemic level is thought to over-ride, or dominate, the acoustic processing in the perception of speech contrasts. Dalebout & Stack believe this explains the difficulties listeners incur with detecting acoustic variations within speech sounds.

Behavioral Measures

The categorical perception of speech has been evaluated primarily by the use of consonants that are varied by such criteria as place of articulation, voice onset time (e.g. Liberman et al., 1957, 1967; Studdert-Kennedy and Shankweiler, 1970; Liberman, 1982) or formant transitions (e.g., Sams et al., 1990; Sharma et al., 1993). Categorical perception refers to a detection of change for a given variable that is not gradual, but is perceived as a discrete category (for review, see Harnard, 1987). Perceptual boundaries arise along a continuum of stimuli, dividing the continuum into discrete regions of
perception (categories), between two or more phonemes. Stimuli within a category are qualitatively similar and differences among acoustically different stimuli in the category may be barely perceptible. However, qualitative differences exist in each across-category stimulus, and will be distinctly perceptible. A categorical boundary is considered to be that point on the continuum at which listeners classify stimuli into categories with equal probability. It is the point corresponding to the fifty percent crossover of the response. The location of a categorical boundary for a given stimulus varies among listeners. In categorical perception studies, a continuum of synthetic stimuli is created between two or more phonemes. Subjects are first required to identify the stimuli as separate categories (e.g. /da/ and /ga/), and then discriminate between the various pairs of stimuli as same or different. Stimuli drawn from the category the listener labeled as “same” are considered to be within-category and stimuli drawn from each of the categories labeled as “different” are across category. The same amount of acoustic difference between stimuli should be distinctly perceptible across categories and may be barely perceptible within the category. Liberman et al. (1957) examined categorical perception of stop consonants and consonant-vowel syllables. Categorical perception was found not to occur when consonants were presented in isolation but did occur when they were presented in vowel context. Also, these experiments demonstrated that for fixed differences in formant frequency, the ability to discriminate was much more accurate across categories than within categories.
Electrophysiological Measures

Research designs in the investigation of speech perception have utilized evoked potentials with various requirements of the subject’s attentional state. The MMN and the P300 have been differentiated by attentional conditions. Dalebout & Stack (1999) suggest that they also may be differentiated by processing levels of speech perception (discussed in the Processing Levels of Speech section); such that MMN may represent the first level (acoustic) processing and P300 may represent the second level (phonetic/phonemic) processing. A typical procedure used to elicit MMN and P300 is the “oddball” paradigm, in which an infrequent stimulus is presented randomly within a series of frequent stimuli.

Mismatch Negativity

The MMN is an automatic, pre-attentive cerebral response to differences in repetitive auditory stimuli sequences (Naatanen, 1992). Studies demonstrate that the MMN originates in the supratemporal auditory cortex with contributions from the auditory thalamus and the hippocampus (Naatanen and Picton, 1987; Kraus et al., 1994). Since it originates from these higher auditory centers, it provides useful information about speech and language processing at the cortical level and it is considered an excellent tool to investigate the neurophysiologic mechanisms of subtle or barely perceivable speech contrasts (Kraus et al., 1995). This event related potential involves a negative voltage shift of electroencephalographic (EEG) activity that typically begins at approximately 100 ms post stimulus onset, and lasts about 200 ms (Maiste et al., 1995). Naatanen et al. (1978) demonstrated that the MMN is elicited using an oddball paradigm in which a train of stimuli (standard) contains an infrequent stimulus (deviant) that differs
in some manner from the others. The standard and deviant stimuli responses are averaged separately and then subtracted, creating a difference waveform (deviant minus standard) where the MMN may be identified. MMN may be recorded by stimulus differences such as changes in intensity, frequency (e.g., Naatanen et al., 1978; Snyder and Hillyard, 1976), duration of tones (e.g., Hari et al., 1984; Kaukoranta et al., 1989), content and direction of frequency glides (Pardo & Sams, 1993), and by changes in speech stimuli (e.g., Aaltonen et al., 1987; Kraus et al., 1992; Sharma et al., 1993).

Kraus et al. (1992) demonstrated that MMN could be elicited in response to stimuli that were from two different categories (perceived behaviorally as /da/ and /ga/). Other investigators have reported that MMN also could be recorded in response to stimuli that were within the same category (Aaltonen et al., 1987; Sharma et al., 1993; Maiste et al., 1995), (e.g., both perceived behaviorally as /da/). The fact that MMN can be recorded in response to CV-stimuli within the same category leads to the suggestion that MMN measures the processing of acoustic features of speech stimuli instead of phonemic features (Aaltonen et al., 1987; Maiste et al., 1995; Sharma et al., 1993; Dalebout & Stack, 1999). Thus, MMN has been suggested to represent the first level of processing hypothesized by Dalebout & Stack (1999).

Sharma et al. (1993) used a synthesized nine item /da/ to /ga/ continuum to elicit MMN from stimuli that had previously been identified behaviorally in a categorical manner by all members involved in the study. The results demonstrated the presence of a MMN in all subjects in both the across-category and within-category conditions. Based on their results, they concluded MMN is a measure of the detection of acoustic properties of speech sounds. Consistent with this, Maiste et al. (1995) evaluated the categorical
processing of spoken speech using a /ba-/da/ continuum. Behaviorally, it was confirmed that the speech stimuli were perceived in a categorical manner. However, for /ba/ as the deviant stimulus, the MMN was absent; MMN was present with /da/ as the deviant stimulus. They proposed this was due to /da/ containing frequency components that were not present in /ba/. This inconsistency did not support categorical processing in the MMN. Based on these results, they concluded that MMN is based on the detection of acoustic differences rather than phonemic categorization.

Aaltonen et al. (1987) used synthesized stimuli on a Finnish vowel continuum where the contrasts included the end points of the /i/ to /y/ continuum and each of the endpoints were presented separately with an intermediate stimulus. The MMN response varied according to the formant frequency differences between the stimulus pairs, not according to categorical differences, suggesting an acoustic detection change instead of a phonemic one.

Stokes (1995) recorded MMN responses to spoken syllables /pa/ and /ba/ for both within and across-categories with varying voice onset times. There were no significant differences noted in the MMN responses to within and across category conditions, supporting an acoustic discrimination ability and an absence of linguistic/categorical processing.

Aaltonen et al. (1993) recorded MMN of patients with left temporal posterior and anterior brain lesions. Those with anterior lesions produced MMN to both pure-tone and vowel stimuli, whereas the posterior-lesioned patients demonstrated MMN to pure-tone stimuli only and not to the vowel stimuli. Behavioral discrimination tasks (same vs. different) using the same stimuli showed that only one patient (anterior-lesioned) out of
all the subjects could discriminate between the vowel stimuli above chance level. This
failure to discriminate behaviorally was inconsistent with the MMN results in the same
subjects, which reflected electrophysiological discrimination. Thus, processes used for
behavioral discrimination may be different or more involved than those being utilized in
the MMN.

P300
An additional auditory event related potential that utilizes the same stimulus
paradigm as the MMN is the P300. In contrast to the MMN, the P300 is not passively
elicited. It requires the listener to actively attend to and discriminate between presented
stimuli. It is a later-occurring potential, which reflects conscious stimulus discrimination
and evaluation (Gaillard & Verduin, 1985). The P300 is positive in polarity and elicited
when subjects are able to discriminate between stimuli on a physical or semantic basis
(Pritchard, 1981). A task is typically associated with identifying the rare stimulus, such
as instructing the listener to count the occurrence of the rare stimulus (Kurtzberg et al.,
1979).

Sams et al. (1990) suggested that P300 might be a reflection of both continuous
(acoustic) and categorical (phonetic) processing modes. Phonetic categorization was
demonstrated in the amplitude characteristics of the P300. Sams et al. (1990)
demonstrated that for an increase in acoustic differences, the P300 amplitude was
unaffected unless the rare stimulus was not in the category of the standard stimuli.
Conversely, speech acoustic processing was reflected in the latency aspect of the P300. In
this study, unlike P300, MMN responses were present to all CV-stimulus contrasts, showing no evidence of categorical perception.

The Aaltonen et al. (1987) study, presented earlier in regard to MMN, also incorporated P300 testing. When the deviant stimulus was the pure vowel /i/ on the Finnish vowel continuum, a shorter latency P300 was produced, without regard to whether the standard stimulus was the pure vowel /y/ or the phoneme boundary. However, when /y/ was the deviant, the P300 responses did not differ from those produced by the boundary stimulus. MMN was found to be present for all CV-stimulus contrasts. The different patterns exhibited between the MMN and the P300 suggest that categorical perception is reflected in the P300 and not in MMN.

Stokes (1995) found that, unlike MMN from the same subjects, the P300 was associated with categorical processing of linguistic stimuli. It was demonstrated that across-category amplitude components were significantly greater than the within-category amplitudes. The latency components indicated no significant differences to within or across-category stimuli.

**Measures of Categorical Perception combining P300, MMN, and Behavioral**

Several studies have combined MMN and behavioral labeling tasks (Aaltonen et al., 1993), MMN and P300 testing (Aaltonen et al., 1987; Maiste et al., 1995), and MMN, P300, and behavioral labeling tasks (Sams et al., 1990; Stokes, 1995) in response to across-category and within-category speech stimuli. Generally results have been consistent with earlier-level detection of acoustic change by MMN and higher-level cognitive recognition of phonemic differences by P300 and behavioral responses.
Sams et al. (1990) and Stokes (1995) incorporated behavioral labeling tasks in which subjects were to identify each CV stimulus as belonging to a category. This was done to identify categorical boundaries and validate the linguistic characteristics of the stimuli utilized in the MMN and P300 measures. Dalebout & Stack (1999) measured MMN, P300, and behavioral responses to CV stimuli. However, the behavioral measures were extended to include a same/different (AX) and an oddball discrimination task. For the oddball task, listeners were instructed to identify a deviant stimulus while listening to a train of CV stimuli. This task was performed simultaneously with the P300. MMN and P300 were obtained by three stimulus contrasts; a) stimulus endpoints, b) a two-step contrast that straddled each listener’s categorical boundary, and c) a within-category contrast (that was not previously differentiated behaviorally by any of the subjects). It was postulated that MMN should be obtained with contrasts that could not be perceived behaviorally if 1) MMN reflects the detection of acoustic differences and 2) the acoustic differences between speech continuum steps are uniform. Results indicated, first, that listeners demonstrated better discrimination ability to the endpoints of the continuum (first stimulus contrast), behaviorally. MMN responses for this condition were present in nine of the twelve subjects, while P300 responses were present in all twelve subjects. For the second contrast condition (two-step contrast), MMN was present in ten of the twelve subjects, while P300 was present in four. For the most difficult condition (within-category), ten of the twelve listeners exhibited a MMN from stimuli that could not be differentiated behaviorally, and none exhibited a P300.

These results generated Dalebout & Stack’s proposition of three processing levels (discussed in the Processing Levels of Speech Section). The presence of a MMN in the
absence of the P300 to the within-category contrast may be a reflection of the auditory mode of processing. If this is an accurate reflection, MMN may be used as an index of neurophysiological discrimination of acoustic parameters in speech perception, not as a correlate to behavioral discrimination abilities. The P300, on the other hand, may reflect a more central, phonetic/phonemic level of processing and may be more likely to correlate with behavioral discrimination abilities. A better understanding of the association between neurophysiological representations and behavioral perceptions of acoustical information may enable hearing scientists and clinicians to more accurately address speech perception and learning disorders.

Rationale of Present Study

This study was designed to test the hypothesis of Dalebout & Stack (1999) by using speech (two within-category stimuli) and non-speech (two frequency glides whose frequencies match the formant transitions of the consonant-vowel stimuli). Responses were measured behaviorally and electrophysiologically (MMN and P300). If MMN is a representation of acoustic processing, and P300 and behavioral responses represent a second level phonemic/phonetic processing and a third level of linguistic processing, respectively, we hypothesize the following in the group average:

1) MMN in response to both stimulus contrasts (speech and non-speech)
2) P300 only to non-speech contrasts
3) Behavioral responses only to non-speech contrasts

We expected to see the first result because detection of acoustic differences in both the speech and non-speech stimuli occurs due to early phases of neural events in the
auditory system regardless of discrimination ability. We expected the latter two results because the speech stimuli were within-category, so they should not be perceived differently. Dalebout & Stack (1999) suggest these within-category differences are not perceived by P300 and behavioral tasks because the phonetic/phonemic level dominates in the perception of speech, and therefore acoustic variations in speech stimuli are not perceptible.
CHAPTER III

Method of Procedure

Participants

Participants consisted of 10 male and female adults (19-35 years of age). Each participant met the following criteria: normal hearing (thresholds of 20 dB HL or less for pure tones at 500, 1000, 2000, 3000, 4000, and 6000 Hz in both ears) as determined by audiometric testing; native English speakers; no known neurological, cognitive, or learning deficits as reported by subjects; and ability to label a continuum of /ba/-/da/ CV stimuli in a way that results in a categorical boundary (see section on Interview/Screening for details).

Stimuli

Stimulus Generation

Speech stimuli were drawn from a nine-item (#1-#9) synthetically-generated continuum of CV stimuli and frequency glides (see Figure 1). For the CV stimuli the vowel /a/ was presented. They were arranged such that stimulus #1 was the most /b/-like, and stimulus #9 was the most /d/-like. The stimuli were generated using the cascade configuration of a PC version of the Klatt synthesizer using a sampling rate of 10 kHz. To enable use of these stimuli with the electrophysiological measures, the total duration of these CV stimuli were 100 ms. During the first 40 ms, the frequency of the first formant (F1) and second formant (F2) were in transition, and the last 60 ms of the syllable represented the vocalic steady-state. The onset frequency of F2 was varied from 900 Hz to 1700 Hz in 100 Hz steps, with an offset frequency of 1250 Hz. These values
**Starting Frequency (Hz)**  **Ending Frequency (Hz)**

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Figure 1. Parameters forming the nine-item continuum for speech (F2 formant transition) and nonspeech (frequency ramp) stimuli.
of F2 are associated with perception of /b/ (900 Hz) and /d/ (1700 Hz). F1 for all stimuli had an onset frequency of 150 Hz, and rise to a steady-state value of 750 Hz in 40 ms. Vocalic steady-state values were as follows: F1=750 Hz, F2= 1200 Hz, F3= 2400 Hz, F4= 3300. The CV stimuli were output from a D/A converter, low-pass filtered at 4.8 kHz, sent to an attenuator, sent to a headphone buffer, and routed to headphones located inside a double-walled sound booth.

Frequency-glide stimuli were generated using a sampling rate of 50 kHz. There was a 5-ms ramp at the onset and offset of each stimulus. Segment 1 of each stimulus consisted of a 40 ms frequency transition glide; Segment 2 consisted of a 60 ms steady tone of 1250 Hz. The two segments overlapped by one ms, seamlessly integrating the two segments into one frequency-glide. The starting frequency for each glide was identical to the F2 onset frequency for the formant transitions in the CV stimuli (900-1700 Hz in 100 Hz steps). These stimuli were output from a D/A converter, low-pass filtered at 4.8 kHz, sent to an attenuator, sent to a headphone buffer, and routed to headphones located inside a double-walled sound booth.

**Process of Stimulus Selection**

Psychophysical labeling and discrimination tasks were performed on seven pilot subjects to determine the most appropriate stimulus contrasts to be utilized in the study. The contrast that was chosen was based on its ability to evoke the greatest detection of difference for non-speech and the least detection of difference for speech. In discrimination tasks to the 2-4 non-speech contrast, on average, listeners detected a difference 66% of the time. However, in the 2-4 speech analog, difference detection
occurred only 6% of the time. Individual responses can be seen in Table 1. Participants labeled speech stimulus item 2 as /ba/ 100% of the time and speech stimulus item 4 as /ba/ 90% of the time (Figure 2). A paired samples t-test on discrimination of the speech vs. non-speech stimuli was significant (df=6, t=5.196, p=.002). Results of the t-test bear out a significant difference in the discrimination of speech vs. non-speech stimuli. In addition, the results for the non-speech discrimination task are similar to the results found in a study examining frequency glide discrimination (Summers & Leek, 1995).

It should be noted these data were collected informally. Two of the subjects (S6 and S7) listened through different headphones than the other participants, and their performances differed significantly from the rest of the listeners. Specifically, they could not hear differences between the 2 and 4 frequency glides. However, based on the overall performance of pilot study participants, the proposed stimuli demonstrated the desired perceptual characteristics.

Interview/Screening

Initially, all participants attended an interview/screening session. During this session: 1) a description of the study was given, including the general purpose, nature of participation and risks and benefits, 2) the written consent form was read and signed (Appendix A), 3) a case history was given, asking specific questions about past and present ear infections, noise exposure, head trauma, and cognitive or learning deficits (Appendix B), 4) the participants received a hearing evaluation, which included audiometric testing, tympanometry, and otoscopy, and 5) a baseline psychophysical labeling measure was obtained to the syllables /ba/ and /da/ for every subject. In this
Table 1: Stimulus Selection with Pilot Data

### Frequency Glides Perceived as Different

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**Mean**

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**Std Dev**

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### CV Stimuli Perceived as Different

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**Mean**

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**Std Dev**

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<td>1.07</td>
<td>1.13</td>
<td>1.25</td>
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Figure 2. Mean labeling of the nine-item speech continuum by seven pilot subjects. Percent /b/ responses are shown as function of F2 onset.
computerized labeling task, each of the nine speech stimuli were presented at a comfortable listening level in randomized order in each of 10 trials. The subjects were asked to identify each stimulus as belonging to one of the two categories (/ba/ or /da/). All stimuli were presented to the right ear. Subjects unable to categorize the stimuli were excluded from the study. At the completion of the interview/screening session, the participants were scheduled for an experimental session.

**Behavioral Studies Procedure**

During the experimental session, each subject performed two computerized, two-alternative, forced-choice, same/different (AX) discrimination tasks, indicating if the two stimuli were the same or different, prior to electrophysiologic testing. With one, pairs of the same stimuli used in the labeling task (syllables /ba/ and /da/) were randomly presented. With the other, random pairs of frequency-glide stimuli were presented. Thirty-five responses were taken with each AX task. The paired stimuli were separated in time by 50 ms. This was followed by the electrophysiological tests.

Behavioral responses also were obtained using an oddball discrimination task. These responses were recorded coincident with P300 data collection (discussed in Auditory Evoked Potentials section). Participants were instructed to listen to a train of stimuli (speech and non-speech) and to press a button upon hearing the deviant (oddball) stimulus. To monitor the attention given to the task, measurements were performed toward the beginning, middle, and end of the P300 collection.

During the psychophysical task, the participants sat in a sound-treated booth. They were instructed to push certain buttons in response to sounds presented monaurally
via supra-aural headphones (Sennheiser, HD 265) in the computerized same/different
discrimination tasks and an insert earphone (Etymotic Research, model ER-3A) for the
oddball discrimination task. All stimuli were presented to the listener at a maximum
RMS of 75 dB SPL in the right ear.

Behavioral Data Analysis

Labeling Criterion Task

Phonemic categorical boundaries corresponding to the 50% point on the
psychometric function and slopes at the boundary were calculated. The 50% point was
determined by linear interpolation, whereas slopes were calculated from the 70% or
greater point of /b/ categorization, to the 30% or less point of /b/ categorization.

Same/Different (AX) Discrimination Task

Percent accuracy of the "same/different" responses were measured in a two-
alternative, forced-choice, same/different (AX) discrimination task in response to speech
and non-speech stimulus pairs. Individual and group grand mean results were analyzed.

Oddball Discrimination Task

The percentage of correct button presses to the random presentation of the rare
stimuli in the oddball paradigm was calculated for the speech and non-speech stimulus
contrasts. Individual and group grand mean results were analyzed.
Statistical Analysis of Behavioral Data

Because of the number of subjects used in this study was less than \(a + 10\), where \(a\) is the number of levels for repeated measures; a multivariate test would be relatively less powerful than the univariate approach (Stevens, 1996). Thus, repeated-measures ANOVAs were used for statistical analyses. For the ANOVAs, the F value from the first test (Pillais) was reported as an approximate F. Significance was found at \(p < 0.05\). The percent of detected difference to the speech and non-speech were used as the dependent variables for computation of a repeated-measures analysis of variances (ANOVA) on the data from the AX discrimination task. The percent correct scores were used as the dependent variables for computation of a repeated-measures multivariate analysis of variances (MANOVA) on the data from the oddball discrimination task. The factor was Stimulus Type (2 levels, speech and non-speech).

Auditory Evoked Potentials Procedure

Two types of AEPs (P300 and MMN) were measured using a 2-channel electrode configuration during the electrophysiological portion of the experimental session. Per subject, three blocks of P300 were measured and nine blocks of MMN were measured, alternately. Alternate blocks of P300 and MMN were intended to avoid subject fatigue and promote attention given to P300 stimulus presentation. Within a type of AEP (P300 or MMN), per subject, the order of presentation of each stimulus contrast was randomized (see Appendix C). A total of six blocks of P300 were obtained from each subject (three using speech stimuli and three using non-speech stimuli) and 18 blocks of MMN were collected (nine using speech stimuli and nine using non-speech stimuli).
The stimulus contrast pairs measured were 1) 2-4 CV and 2) 2-4 frequency glide. Using the oddball paradigm, the first stimulus in each pair was the standard and the second was the deviant with a probability of occurrence of 0.85 and 0.15, respectively. The interstimulus interval (from onset of stimulus one to onset of stimulus two) was 900 ms. Three trial blocks were collected per stimulus contrast for P300 and nine trial blocks were collected per stimulus for MMN, with each trial block taking approximately five minutes. Within a block, single trial AEPs elicited by 170 standard stimuli were averaged separately from single trial AEPs elicited by 30 deviant stimuli, resulting in two waveforms for the standard stimuli (from electrodes at A1 and A2) and two waveforms for the deviant stimuli (from electrodes at A1 and A2) per block. For each subject, responses obtained during the trial blocks for a given AEP with the same stimulus contrast were averaged together off-line, again keeping standard and deviant waveforms separate. For P300, this resulted in a total number of 510 averages to the standard and 90 averages to the deviant for each of the two electrode sites. For MMN, a total of 1530 averages to the standard and 270 averages to the deviant resulted for each of the two electrode sites. Averages were baseline corrected using mean amplitudes obtained during the pre-stimulus period (0-50 ms). For each AEP type and stimulus contrast a difference waveform was obtained by subtracting the standard waveform from the deviant waveform.

Gold-plated electrodes were applied to the surface of the scalp. Prior to electrode placement, the skin was cleansed with a mild facial scrub and a conductive paste was applied. The electrodes were held in place with medical tape. Electrode impedances were measured at 30 Hz and were below 5k and within 1k of each other. The non-inverting
electrode was placed on the vertex of the head (Cz), the inverting electrodes were on the
earlobes (A1 & A2), and the ground electrode on the forehead (Fpz) (Jasper, 1958). The
electro-oculogram (EOG) was used to develop an eye-blink rejection rule for each
subject. The EOG was recorded between electrodes above and below one eye and
amplified (gain: 1x10$^4$). Artifact reject for the EOG was set to exclude sweeps collected
during eye-blinks or muscle contractions. Before data collection began, participants were
asked to blink naturally 10 times. The smallest deflection caused by that individual’s
blink was recorded and the artifact reject set to match it. Eye blinks were also monitored
via video surveillance. The AEPs were differentially amplified (gain: 1 x 10$^5$) (Tucker-
Davis Technologies, model DB4) and filtered. The rejection rate of these filters was -6
dB/octave. The bandwidths were DC-30 Hz. An artifact rejection algorithm was applied
to the online averaging waveform. If the peak voltage within a sweep exceeded ± 80 µV,
that sweep was excluded from the averaged waveform. Custom software copyrighted by
the regents of the University of Texas at Austin was used for acquisition of all data. Each
response was digitized over a 550-ms sweep duration beginning 50 ms before stimulus
onset via a 16-bit analog-to-digital converter (Tucker-Davis Technologies, model AD2).
A total of 256 points were averaged in a 550 ms time window, resulting in a sampling bin
of 2.15 ms.

During the recording session, each participant sat in a sound-treated booth,
comfortably reclined in an armchair with his/her head and neck well supported. Stimuli
were delivered monaurally through an electrically-shielded insert earphone (Etymotic
Research, model ER-3A). The level of the stimuli was 75 dB peak SPL. Based on
random assignment, channel 1 was ipsilateral in half of the ears tested and channel 2 was
ipsilateral in the other half. During the recording session, participants were instructed to sit quietly, but not sleep. During P300 recordings, participants were instructed to press a button in response to the deviant stimuli, while during the MMN recordings, they watched a silent videotaped movie with closed captioning. The participants were given frequent breaks.

**Electrophysiological Data Analysis**

**MMN**

Individual mean waveforms and group grand mean waveforms were analyzed as described below. N1 and P2 of the LLR were obvious in both the standard and deviant waveforms and were identified from the standard waveform to be used as a reference for labeling MMN. LLR and MMN peaks were identified based on response windows in previously reported literature (e.g., Martin et al., 1999). The response window for N1 was 80 – 200 ms and P2 was identified as the greatest positive peak following N1. The MMN response window was 80 – 400 ms. MMN, when present, was evident only in the deviant and difference waveforms. For each stimulus contrast, MMN onset and offset latencies were identified from the grand mean standard and deviant waveforms and applied to the evaluation of individual waveforms. Onset latency was defined as the positive peak immediately preceding the visually defined maximum point of negativity. Offset latency was the positive peak immediately following the maximum point of negativity. Thus, for each stimulus contrast, a fixed MMN duration was calculated from the grand mean waveforms (offset minus onset latency) and applied to all individual difference waveforms evoked by that stimulus contrast. Peak latency and mean
amplitude were obtained from individual and grand mean difference waveforms. Peak latency was defined as the maximum point of negativity following the N1 component (identified in the standard waveform). Mean amplitude was calculated by averaging the amplitudes for the defined duration of the individual difference waveforms. Each waveform was analyzed by the experimenter using Excel (Microsoft) and Sigma Plot 5.0 (SPSS) software.

P300

Individual mean waveforms and group grand mean waveforms were analyzed. N1 and P2 of the LLR were obvious in both the standard and deviant waveforms and were identified from the standard waveform to be used as a reference for labeling P300. LLR and P300 peaks were identified based on response windows in previously reported literature (e.g., Dalebout and Stack, 1999). The response window for N1 was 80 - 200 ms, P2 was identified as the greatest positive peak following N1, and N2 (when present) was the greatest negative peak following P2. The P300 response window was 200 - 500 ms. P300, when present, was evident only in the deviant and difference waveforms. For each stimulus contrast, the onset latency and offset latency of P300 was identified from the grand mean waveforms and then applied to individual difference waveforms. Onset latency was defined as the negative peak immediately preceding the visually defined maximum point of positivity (P2). Offset latency was the negative peak immediately following the maximum point of positivity. Thus, for each stimulus contrast, P300 duration was calculated from the grand average waveforms (offset minus onset latency) and then applied to all individual difference waveforms for that stimulus contrast. Peak
latency, mean amplitude and peak-to-peak amplitude were obtained from individual and grand mean difference waveforms. Peak latency was defined as the maximum point of positivity following the P2 component (identified in the standard waveform). Mean amplitude was calculated by averaging the amplitudes for the defined duration of the individual difference waveforms. P300 peak-to-peak amplitude was calculated by taking the amplitude difference of the peak and the successive trough. Each waveform was analyzed by the experimenter using Excel (Microsoft) and Sigma Plot 5.0 (SPSS) software.

**Statistical Analysis for Electrophysiological Data**

ANOVA were performed on each of the dependent variables measured from speech-evoked and frequency glide-evoked AEPs to determine if the waveforms differed at each electrode site. The factor was side (2 levels; ipsilateral, contralateral). A finding of no significant differences between responses obtained from the ipsilateral versus contralateral electrodes for any of the dependent variables would permit all remaining statistical analyses to be performed on ipsilateral measures. For all ANOVAs, the F value from the first test (Pillais) was reported as an approximate F and significance was found at $p<0.05$ level. The peak-to-peak amplitude, peak latency, and mean amplitude were used as the dependent variables for computation of three one-factor repeated measures ANOVAs for the P300 data. The latency and mean amplitude measures were used as the dependent variables for computation of two one-factor repeated-measures ANOVAs for the MMN data. The factor was Stimulus Type (2 levels, speech and non-speech). Graphs were used to follow up significant main effects or interactions.
CHAPTER IV

Results

This primary purpose of this project was to examine the relationship between auditory evoked potentials (AEPs) and psychophysical responses to linguistic and non-linguistic stimuli. The responses were used to detect the presence, if any, of differential processing to non-speech (frequency glides) and speech (consonant-vowel) stimuli. Additionally, an investigation of the viability of using MMN as a measure of acoustical difference detection, and P300 and behavioral responses as a measure of phonemic/phonetic processing was probed to further examine the hypothesis put forth by Dalebout & Stack (1999). Thus, the dependent variables of interest included stimulus type for the same/different discrimination task, stimulus type and trial for the oddball discrimination task, the peak-to-peak amplitude, peak latency, and mean amplitude of the P300, and latency and mean amplitude of the MMN, both to glides and speech.

Behavioral Results

Labeling Criterion Task

Speech stimulus item 2 was labeled as /ba/ 100% of the time and item 4 was labeled as /ba/ 98% of the time in the group mean. All participants labeled the /ba/ to /da/ continuum in a way that resulted in a categorical boundary. Individual and mean categorical boundaries and slopes at the boundaries can be seen in Table 2. Individual labeling functions can be seen in Appendix D.
Table 2: Labeling Criterion Task

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<th>Subject</th>
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<th>Slope</th>
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<td>Subject 2</td>
<td>1300</td>
<td>-3.2</td>
</tr>
<tr>
<td>Subject 3</td>
<td>1357</td>
<td>-1.4</td>
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<tr>
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<tr>
<td>Std Dev</td>
<td>61.3</td>
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Note. Categorical boundary corresponds to the 50% point on the psychometric function in reference to the F2 onset frequency.
Same/Different (AX) Discrimination Task

The individual and mean percent accuracy scores to the non-speech frequency glides and CV speech stimuli are displayed in Table 3. Listeners exhibited the best discrimination to the non-speech, 2-4 contrast, on average, detecting a difference 64% of the time. Listeners displayed poorer ability in difference detection of the speech, 2-4 contrast, on average detecting a difference 8% of the time. In a one-factor repeated measures ANOVA, stimulus type was found to be significant (F= 45.231, p= 0.00) (Table 4).

Oddball Discrimination Task

Individual and mean percent correct button presses to the random presentation of the rare stimuli in the oddball paradigm can be seen in Table 5. The group mean percent correct button presses was 82% for the non-speech stimulus contrast. For the speech stimulus contrast, the group mean percent correct button presses was 46% across the three trials. Results for the two-factor, repeated measures MANOVA (Table 7) indicated a significance (F= 17.418, p=0.002) for stimulus type and trial (F= 7.342, p=0.015). There was no significant interaction. Overall, subjects were better at discriminating between the non-speech versus the speech stimuli. Generally, there was slight improvement in discrimination of both types of stimuli from Trial One to Trial Three.

Electrophysiological Results

MMN

N1 and P2 of the LLR were obvious in both the standard and deviant waveforms. A measurable MMN was present in response to both non-speech glides and CV speech stimuli in the deviant and difference waveforms of all subjects. For guidance, individual MMN responses were examined based on onset, offset, and duration measures obtained
Table 3: Percentage Accuracy in the Same/Different (AX) Discrimination Task

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<th>Speech CV</th>
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<td>Subject 10</td>
<td>40</td>
<td>0</td>
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Mean | 64 | 8 |
Std Dev | 26.3 | 14.0 |

Note. Each trial is out of a possible 100% detected difference.
Table 4: Statistical Results from 1 Factor Repeated Measures ANOVA of Same/Different Discrimination Task

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Note. Factor = Stimulus Type (2 levels).
Table 5: Percent Correct Button Presses for the Oddball Discrimination Task

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<tr>
<th></th>
<th>Non-Speech (Glides)</th>
<th></th>
<th></th>
<th></th>
<th>Speech (CV)</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Trial 1</td>
<td>Trial 2</td>
<td>Trial 3</td>
<td>Mean</td>
<td>Trial 1</td>
<td>Trial 2</td>
<td>Trial 3</td>
<td>Mean</td>
<td></td>
</tr>
<tr>
<td>Subject 1</td>
<td>96.7</td>
<td>96.7</td>
<td>100.0</td>
<td>97.8</td>
<td>60.0</td>
<td>66.7</td>
<td>76.7</td>
<td>67.7</td>
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</tr>
<tr>
<td>Subject 2</td>
<td>63.3</td>
<td>56.7</td>
<td>43.3</td>
<td>54.4</td>
<td>0.0</td>
<td>16.7</td>
<td>16.7</td>
<td>11.0</td>
<td></td>
</tr>
<tr>
<td>Subject 3</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>43.3</td>
<td>70.0</td>
<td>73.3</td>
<td>62.3</td>
<td></td>
</tr>
<tr>
<td>Subject 4</td>
<td>100.0</td>
<td>100.0</td>
<td>96.7</td>
<td>98.9</td>
<td>56.7</td>
<td>56.7</td>
<td>70.0</td>
<td>61.0</td>
<td></td>
</tr>
<tr>
<td>Subject 5</td>
<td>83.3</td>
<td>73.3</td>
<td>90.0</td>
<td>82.2</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>Subject 6</td>
<td>93.3</td>
<td>100.0</td>
<td>100.0</td>
<td>97.7</td>
<td>73.3</td>
<td>63.3</td>
<td>80.0</td>
<td>72.3</td>
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<tr>
<td>Subject 7</td>
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<td>90.0</td>
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<td>76.7</td>
<td>0.0</td>
<td>33.0</td>
<td>0.0</td>
<td>1.0</td>
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</tr>
<tr>
<td>Subject 8</td>
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<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>70.0</td>
<td>100.0</td>
<td>28.0</td>
<td>93.3</td>
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</tr>
<tr>
<td>Subject 9</td>
<td>16.7</td>
<td>6.7</td>
<td>23.3</td>
<td>15.7</td>
<td>26.7</td>
<td>30.0</td>
<td>30.0</td>
<td>29.0</td>
<td></td>
</tr>
<tr>
<td>Subject 10</td>
<td>100.0</td>
<td>90.0</td>
<td>100.0</td>
<td>96.7</td>
<td>43.3</td>
<td>56.7</td>
<td>86.7</td>
<td>62.3</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>81.6</td>
<td>81.3</td>
<td>83.0</td>
<td>82.0</td>
<td>37.3</td>
<td>49.3</td>
<td>46.1</td>
<td>46.0</td>
<td></td>
</tr>
<tr>
<td>Std Dev</td>
<td>29.5</td>
<td>38.1</td>
<td>32.9</td>
<td>29.3</td>
<td>17.4</td>
<td>20.2</td>
<td>31.6</td>
<td>12.8</td>
<td></td>
</tr>
</tbody>
</table>

Note. Each trial is out of a possible 100% correct button presses.
Table 6: Statistical Results from 2 Factor Repeated Measures MANOVA of Oddball Discrimination Task

<table>
<thead>
<tr>
<th>Factor</th>
<th>Pillai's F</th>
<th>Hypothesis df</th>
<th>Error df</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stimulus Type</td>
<td>17.418</td>
<td>1.0</td>
<td>9.0</td>
<td>0.002</td>
</tr>
<tr>
<td>Trial</td>
<td>7.342</td>
<td>2.0</td>
<td>8.0</td>
<td>0.015</td>
</tr>
<tr>
<td>Interaction</td>
<td>2.313</td>
<td>2.0</td>
<td>8.0</td>
<td>0.161</td>
</tr>
</tbody>
</table>

Note. Factors= Stimulus type (2 levels) and Trial (3 levels). Dependent Variable = % accuracy in oddball discrimination task.
from the grand average waveforms. For the MMNs evoked by frequency glides, onset latency was 141.2 ms, offset latency was 261.4 ms, and duration was 120.2 ms. Grand mean waveforms for frequency glides are shown in Figures 3 and 4. For the MMNs evoked by speech, onset latency was 98.02, offset latency was 340.9 ms, and with the resulting duration of 242.7 ms. Grand mean waveforms for speech are shown in Figures 5 and 6. Individual MMN waveforms can be found in Appendix E. Individual and mean values for the 2 dependent variables (mean amplitude and latency) can be found in Table 7.

Two one-factor repeated measures ANOVAs were performed on each of the dependent variables measured from speech-evoked MMNs and each of the dependent variables measured from frequency glide-evoked MMNs. The factor was side (2 levels; ipsilateral, contralateral). No significant differences between responses obtained from the ipsilateral versus contralateral electrodes were found for any of the dependent variables. Thus, all remaining statistical analyses were performed on ipsilateral MMN measures.

Two one-factor repeated measures ANOVAs were performed; one on MMN peak latency, and one on MMN mean amplitude. The factor was stimulus type (2 levels: speech, non-speech). No significance was found with the ANOVA for MMN peak latency ($F_{1,9} = 0.055; p = 0.82$) or MMN mean amplitude ($F_{1,9} = 2.453; p = 0.15$), indicating these MMN measures were not different when evoked from CV speech versus non-speech glide stimuli (Table 8).

P300

N1 and P2 of the LLR were obvious in both the standard and deviant waveforms of all participants. A P300 was present in response to the non-speech stimuli in the deviant and difference waveforms for all listeners, but was not present in most cases for the speech stimuli. For guidance, individual P300 responses were examined based on
Figure 3. Grand mean MMN responses to non-speech frequency glides. The thick lines represent the response to the deviant stimuli and the thin lines to the standard stimuli. The left panel is the ipsilateral response and the right is the contralateral response.

Figure 4. Grand mean MMN difference waveforms in response to non-speech frequency glides. The left panel is the ipsilateral response and the right is the contralateral response. Measures obtained from the ipsilateral electrode include the following: onset= 141.2 ms, offset= 261.4 ms, duration= 120.2 ms, latency= 209.9 ms, and mean amplitude= -0.032 microV.
Figure 5. Grand mean MMN responses to CV speech. The thick lines represent the responses to the deviant stimuli and the thin lines to the standard stimuli. The left panel is the ipsilateral response and the right is the contralateral response.

Figure 6. Grand mean MMN difference waveforms in response to CV speech. The left panel is the ipsilateral response and the right is the contralateral response. Measures obtained form the ipsilateral electrode include the following: onset= 98.2 ms, offset= 340.9 ms, duration= 242.7 ms, latency= 278.6 ms, and mean amplitude= -0.0046 microV.
Table 7: Descriptive Statistics for Auditory Evoked Potentials

<table>
<thead>
<tr>
<th></th>
<th>NON-SPEECH GLIDES</th>
<th>MMN</th>
<th>CV SPEECH</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean Amplitude</td>
<td>Mean Amplitude</td>
<td>Mean Amplitude</td>
</tr>
<tr>
<td>N</td>
<td>Ipsi</td>
<td>Contra</td>
<td>Ipsi</td>
</tr>
<tr>
<td>Mean</td>
<td>-0.71</td>
<td>-0.02</td>
<td>213.76</td>
</tr>
<tr>
<td>Std. Deviation</td>
<td>0.13</td>
<td>0.03</td>
<td>19.47</td>
</tr>
<tr>
<td>Minimum</td>
<td>-0.40</td>
<td>-0.10</td>
<td>171.20</td>
</tr>
<tr>
<td>Maximum</td>
<td>0.00</td>
<td>0.00</td>
<td>240.00</td>
</tr>
</tbody>
</table>

|                | NON-SPEECH GLIDES | P300            | CV SPEECH       |
|                | Mean Amplitude    | Mean Amplitude | Mean Amplitude |
| N              | Ipsi              | Contra          | Ipsi            | Contra          | Ipsi | Contra |
| Mean           | 0.63              | 0.59            | 0.03            | 0.01            | 0.28 | 0.32   |
| Std. Deviation | 0.39              | 0.43            | 0.06            | 0.08            | 0.09 | 0.13   |
| Minimum        | 0.20              | 0.10            | -0.10           | -0.10           | 0.10 | 0.10   |
| Maximum        | 1.40              | 1.50            | 0.10            | 0.10            | 0.40 | 0.50   |


Table 8: Statistical Results of AEPs from 1 Factor Repeated Measures ANOVA

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>Pillai's F</th>
<th>Hypothesis df</th>
<th>Error df</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>MMN Mean Amplitude</td>
<td>2.453</td>
<td>1.0</td>
<td>9.0</td>
<td>0.152</td>
</tr>
<tr>
<td>MMN Latency</td>
<td>0.055</td>
<td>1.0</td>
<td>9.0</td>
<td>0.820</td>
</tr>
<tr>
<td>P300 Latency</td>
<td>12.767</td>
<td>1.0</td>
<td>9.0</td>
<td>0.006</td>
</tr>
<tr>
<td>P300 Peak to Peak Amplitude</td>
<td>9.228</td>
<td>1.0</td>
<td>9.0</td>
<td>0.014</td>
</tr>
<tr>
<td>P300 Mean Amplitude</td>
<td>0.464</td>
<td>1.0</td>
<td>9.0</td>
<td>0.530</td>
</tr>
</tbody>
</table>

Note. Data is from ipsilateral electrode. Factor = Stimulus Type (2 levels)
onset, offset, and duration measures obtained from the grand average waveforms. For the P300s evoked by non-speech frequency glides, onset latency was 216.3 ms, offset latency was 409.6 ms, and duration was 193.3 ms. Grand mean waveforms for frequency glides are shown in Figures 7 and 8. For the P300s evoked by CV speech, onset latency was 250.7 ms, offset latency was 450.4 ms, and with the resulting P300 duration of 199.7 ms. Grand mean waveforms for speech are shown in Figures 9 and 10. Individual and mean values for the three dependent variables (peak-to-peak amplitude, mean amplitude, and latency) can be found in Table 7.

One-factor, repeated measures ANOVAs were performed on each dependent variable measured from frequency glide evoked P300s and speech evoked P300s. The factor was side (2 levels; ipsilateral, contralateral). No significant differences between responses obtained from the ipsilateral versus contralateral electrodes were found for any of the dependent variables. Thus all remaining statistical analyses were performed on ipsilateral P300 measures.

For each dependent variable, one-factor repeated measures ANOVAs were performed (Table 8). The factor was stimulus type (2 levels; speech, non-speech). For peak-to-peak amplitude, significance was found for stimulus type ($F_{1,9} = 9.228; p = 0.014$), indicating greater amplitude to the glides versus CV stimuli. For P300 peak latency, a significant main effect of stimulus type was found ($F_{1,9} = 12.767; p = 0.006$), indicating that peak latency was earlier when the P300 was evoked by frequency glides versus speech stimuli. No significant main effect was found for P300 mean amplitude ($F_{1,9} = 0.464; p = 0.53$).
Figure 7. Grand mean P300 responses to non-speech frequency glides. The thick lines represent the responses to the deviant stimuli and the thin lines to the standard stimuli. The left panel is the ipsilateral response and the right is the contralateral response.

Figure 8. Grand mean P300 difference waveforms in response to non-speech frequency glides. The left panel is the ipsilateral response and the right is the contralateral response. Measures obtained from the ipsilateral electrode include the following: onset= 216.3 ms, offset= 409.6 ms, duration= 193.3 ms, peak-to-peak amplitude= 0.045 microV, and mean amplitude= 0.029 microV.
Figure 9. Grand mean P300 responses to non-speech frequency glides. The thick lines represent the responses to the deviant stimuli and the thin lines to the standard stimuli. The left panel is the ipsilateral response and the right is the contralateral response.

Figure 10. Grand mean P300 difference waveforms in response to CV speech. The left panel is the ipsilateral response and the right is the contralateral response. Measures obtained from the ipsilateral electrode include the following: onset= 250.7 ms, offset= 450.4 ms, duration= 199.7 ms, peak-to-peak amplitude= 0.045 microV, and mean amplitude= 0.031 microV.
Correlations Between Behavioral and AEP measures

Pearson-product correlations were calculated between various behavioral and AEP measures (Table 9). Generally, correlations were non-significant. One exception was the correlation between P300 peak latency and mean percent discrimination obtained during the oddball task ($r = -0.64$).
Table 9: Correlations between Behavioral and AEP Measures

<table>
<thead>
<tr>
<th></th>
<th>Glides</th>
<th>Speech</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MMN Latency</td>
<td>MMN Latency</td>
</tr>
<tr>
<td>AX</td>
<td>0.274</td>
<td>-0.036</td>
</tr>
<tr>
<td></td>
<td>MMN Mean Amplitude</td>
<td>MMN Mean Amplitude</td>
</tr>
<tr>
<td></td>
<td>-0.047</td>
<td>-0.047</td>
</tr>
<tr>
<td></td>
<td>P300 Latency</td>
<td>P300 Latency</td>
</tr>
<tr>
<td></td>
<td>0.291</td>
<td>0.441</td>
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<tr>
<td></td>
<td>P300 Mean Amplitude</td>
<td>P300 Mean Amplitude</td>
</tr>
<tr>
<td></td>
<td>0.327</td>
<td>0.327</td>
</tr>
<tr>
<td></td>
<td>P300 Peak-to-Peak Amplitude</td>
<td>P300 Peak-to-Peak Amplitude</td>
</tr>
<tr>
<td></td>
<td>-0.469</td>
<td>-0.247</td>
</tr>
</tbody>
</table>

Notes. *= p < 0.05 level (2 tailed), AX= Same/Different Discrimination Task, Mean Oddball Discrimination is collapsed across the three trials.
CHAPTER V

Discussion

Summary of Results in Relation to Hypothesis

Behavioral performance, MMN, and P300 responses were measured using linguistic and non-linguistic stimuli to test the premise put forth by Dalebout & Stack (1999) that these two types of stimuli are processed by different levels of the auditory system. As hypothesized in the rationale of the study (Chapter 2), the following was seen in the group average:

1) Behavioral responses present to non-speech contrasts.
2) MMN in response to both speech and non-speech stimulus contrasts.
3) P300 present to non-speech contrasts.

Behavioral Performance

Overall, the data presented here is consistent with the findings of other categorical perception studies (e.g. Liberman et al., 1957, 1967; Studdert-Kennedy and Shankweiler, 1970) that report poor discrimination of speech sounds that are identified as the same phoneme (within-category), despite the fact that the acoustic differences between these stimuli are the same as the acoustic differences between across-category stimuli. Further, this study demonstrated that the non-speech glides are easily discriminated even though they have the same acoustic differences as the within-category CV speech stimuli, suggesting different auditory processing pathways for each stimulus type. The AEP results are consistent with this suggestion.

Among the behavioral measures, the oddball discrimination task displayed better detection of difference to the speech stimuli than the AX task (Table 10). Although the stimuli used were the same, more than half of the listeners who could not detect a difference in the 2-4 speech contrast in the AX task, were able to hear the difference
Table 10: Comparison between Behavioral Performance and AEP Identification

<table>
<thead>
<tr>
<th>Non-Speech Glides</th>
<th>CV Speech</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AX (%)</td>
</tr>
<tr>
<td>Subject 1</td>
<td>20.0</td>
</tr>
<tr>
<td>Subject 2</td>
<td>80.0</td>
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<tr>
<td>Subject 3</td>
<td>80.0</td>
</tr>
<tr>
<td>Subject 4</td>
<td>40.0</td>
</tr>
<tr>
<td>Subject 5</td>
<td>100.0</td>
</tr>
<tr>
<td>Subject 6</td>
<td>60.0</td>
</tr>
<tr>
<td>Subject 7</td>
<td>60.0</td>
</tr>
<tr>
<td>Subject 8</td>
<td>100.0</td>
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<tr>
<td>Subject 9</td>
<td>60.0</td>
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<td>Subject 10</td>
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<tr>
<td>Mean</td>
<td>64.0</td>
</tr>
<tr>
<td>Std Dev</td>
<td>26.3</td>
</tr>
</tbody>
</table>

Notes. Mean % for oddball is collapsed across the three trials. The presence of an AEP response is indicated by a "+" symbol.
between the same stimuli in the oddball task. Carney et al. (1977) showed that, with training, a break-down in categorical perception could occur such that discrimination within a listener's category is exhibited. Consistent with this finding, significance was noted in this study across the three trials of the oddball discrimination task (Table 4), suggesting a learning effect may have occurred. If listeners were able to break-down their boundary, this could also explain the unexpected presence of P300s in response to the within-category speech stimuli in four of the ten listeners (Table 9; Subject 1, 3, 6, 7). However, this does not explain why P300 was absent in one subject who was able to discriminate difference during the oddball task but not the AX task (Subject 10).

**MMN**

All listeners exhibited an identifiable MMN in response to both frequency glides and speech. In other words, MMN was evoked by non-speech frequency glide contrasts that were perceived as different, but also by CV speech contrasts that were perceived as the same. This is similar to other investigators who reported MMN could be recorded to stimuli that were within the same category (Aaltonen et al., 1987; Sharma et al., 1993; Maiste et al., 1995; Stokes, 1995). These authors concluded that MMN measures the auditory system's detection of acoustic differences, not phonemic differences, and the results obtained in this study are in accord with this conclusion.

The failure to find significance in the MMN latency and mean amplitude measures to speech and non-speech suggests that, at this level of processing, there is no differentiation between the ways the signals are processed. In other words, the detection at this level is acoustical and there is no importance placed on phonemic/phonetic differences.
P300

Nine of ten subjects displayed a P300 in response to the non-speech frequency glides, whereas, only four of ten exhibited a response to CV speech. This finding also supports the proposition of different levels of sound processing. Since all subjects displayed MMNs, the absence of P300s and behavioral discrimination in the majority of subjects for within-category CV speech stimuli would suggest the processing responsible for differentiating acoustic contrasts is active but the level responsible for phonetic contrast differentiation is not. Perhaps, although differences are detected at some lower physiological level, they were not brought to consciousness because of some over-riding mechanism in the processing of speech in the P300. This is consistent with the findings of Dalebout & Stack (1999) who reported presence of MMN and absence of P300 in response to contrasts that were not differentiated behaviorally.

The significance of stimulus type (non-speech vs. speech) found for P300 latency and peak-to-peak amplitude suggests that processing differences are occurring at the level of the P300 and not at the level of MMN. Peak latency for frequency glides occurred earlier than speech, suggesting that glides were more salient and processed faster than the speech stimuli. However, this conclusion is necessarily limited by the small number of P300s evoked in response to the speech stimuli.

Peak-to-peak amplitude proved to be larger for non-speech glides versus CV speech. This is consistent with the results presented by Stokes (1995) in which the presence of P300 in response to speech stimuli is related to categorical perception. In that study, P300 amplitude also proved to be greater for the perceptually discriminable (across-category speech) stimuli.

Research from other investigators has suggested that P300 is a measure of phonetic/phonemic processing modes as well as a reflection of acoustic processing modes (Sams et al., 1990; Aaltonen et al., 1987; Stokes, 1995). These researchers suggest
that phonetic categorization may be defined in the amplitude domain and acoustic processing may be defined in the latency domain. The results of this study may be indicative of this. That is, the significance found for P300 peak latency may also represent differential acoustic processing occurring in both the speech and non-speech stimuli. Perhaps some type of serial processing is illustrated in the shorter latency measures for the non-speech frequency glides. However, this conclusion is limited by the fact that P300 responses measured to CV speech were less frequent than non-speech frequency glides (four to speech vs. nine to non-speech).

**Relation Between Behavioral Performance and Presence of MMN and P300**

The relationship between behavioral performance and AEP presence is summarized in Table 10. The AX and oddball behavioral discrimination performance was good for the glides and extremely poor for the speech. In the non-speech glide contrast, seven of ten listeners had percent correct responses of 60% or higher in the AX and oddball tasks. Of those listeners, all ten exhibited MMN and nine exhibited P300 responses. In the CV speech contrast, none of the ten listeners had percent correct responses above 60% in the AX task, while six of the ten correctly discriminated above 60% in the oddball task. All of the listeners demonstrated MMN responses and only four of ten had identifiable P300s.

When compared to the behavioral responses, MMN did not seem to predict performance in the AX or oddball discrimination task. For each stimulus type, the ability to detect a difference behaviorally was not related to the presence of the MMN. However, the presence of the MMN is suspected to be an indicator that the neurophysiological processes necessary for the behavioral discrimination is there, and with the appropriate training they may be brought to consciousness (Kraus & Cheour, 2000).
As mentioned earlier, with the significance noted across trials in the oddball task, listeners may have been able to break down their categorical boundary to the stimuli that had previously been within-category. Therefore, a difference that may not have been perceptible initially became more easily perceptible with training. Since the oddball discrimination was performed three times coincident with P300 collection, this could explain the presence of P300s in response to the CV speech stimuli in four of the ten listeners.

As presented in Chapter One, the MMN response is thought to originate in the supratemporal auditory cortex and the hippocampus (Naatanen and Picton, 1987; Kraus et al., 1994), while the auditory P300 is thought to be generated from the frontal lobe, hippocampus, and the auditory cortex (for review, see McPherson, 1996; Buchwald, 1990). Considering this in relation to the results reported in this study, it is speculated that these stimuli are being processed in a serial manner. In other words, the generators of the MMN, although occurring in the cortex, may be at a lower level or be considered not as meaningful as the processing measured by the P300 and/or behavioral responses. P300 responses were judged to be indicative of a higher phonetic/phonemic processing level, while behavioral responses were thought to reflect phonetic/phonemic processing and perhaps an even higher-order linguistic processing level (although linguistic processing was not tested in this study).

**Scalp Distribution**

The right ear-advantage for speech stimuli was expected to possibly demonstrate more robust contralateral AEP recordings. The fact that no differences were found between right and left electrode sites as a function of right ear stimulation may be attributed to the poor place-specificity of the 2-channel electrode configuration used. More electrodes would have made any laterality effects measurable.
Means for Objective Analysis

Due of the wide variability of responses observed in the individual MMN and P300 waveforms, it became necessary to define onset, offset, and duration from the grand mean waveforms to maintain consistency in interpreting responses. However, this may have nullified valuable individual characteristics. For example, the significance found in peak-to-peak amplitude, but not mean amplitude suggests that, for the purposes of this study, peak-to-peak amplitude was a more useful measure than mean amplitude. The necessity of assigning a defined onset, offset, and duration may have negated the value of the mean amplitude measure. Within the set duration, for some individual waveforms, there may have been some negativity that counteracted any P300 positivity.

Various methods of identifying MMN have been used by researchers, including area (µV x ms) calculations (e.g., Kraus et al., 1993a, Sharma et al., 1993), mean amplitude measures (e.g., Aaltonen et al., 1994; Maiste et al., 1995), and median methods (Fox & Daleboult, 2001). These researchers agree these methods, in their present form, may be insufficient in consistently identifying MMN responses. The variability of these measures in identifying MMN illustrates the need for determining a universal method to objectively and uniformly measure these types of AEPs.

Processing Dependence on Stimulus Type

Similar to this study, a report by Jarmillo et al. (2001) found speech and non-speech stimuli to be processed differently. Speech stimuli (vowels) proved to elicit a larger MMN and P300 than non-speech (harmonic tones). This was hypothesized to represent the enhanced processing to speech features that carry more meaning in communication and language. This would lend support to the motor theory in speech perception that assumes “speech is special”. If true, then the phonetic/phonemic level thought to over-ride the acoustic processing in speech perception would occur in response
to speech. The assumption that “speech is special” infers that distinct and separate central processors are responsible for signal transmission of speech and non-speech signals. Consequently, as presented in Chapter Two, Dalebout & Stack believe this explains the difficulties listeners encounter with detecting acoustical variations within speech categories.

**Clinical Implications**

Based on the findings of these data, the use of MMN as a clinical tool holds great potential as an objective measure of perceptual capabilities. The presence of MMN in all subjects, despite inabilities to behaviorally discriminate between the stimuli, may represent the capability of the auditory system to be trained to hear acoustic differences. The display of improved discrimination over three oddball trials and the appearance of a P300 in some listeners suggests that training a listener may not take numerous and/or intense training sessions. Neurophysiologic changes in response to behavioral training have been documented in listeners over only a few sessions (Kraus et al., 1995). These researchers trained listeners to detect differences in speech contrasts in six one-hour sessions over the period of one week. The effects of the training were measured one month after the last training session, and were found to be very stable. By measuring MMN and P300, this may be a unique way to assess therapeutic efforts in individuals who exhibit trouble in the discrimination/processing of speech.

In considering the implications with regard to differential processing of speech versus non-speech stimuli, individuals with absent MMN responses may exhibit difficulty discriminating certain sounds but not others. Thus, if a certain region of the brain exhibits poor discrimination performance, another region may exhibit enhanced discrimination.
The drawback to the application of these AEP measures, with regard to this study, is the large amount of individual variability observed in subjects. At the group level, the measures may exhibit great utility as a tool to understand neurologic processes, but the responses of individuals vary greatly, particularly for MMN. Before broad-based acceptance of these AEP measures can be implemented the objective analysis of the response needs to be refined.

Future Research

Considering these data represent listeners with the ability to label acoustic stimuli in a categorical manner, it would be interesting to similarly evaluate the responses of normal hearing individuals that lack that ability. In a follow-up study, discrimination training could be implemented and behavioral and AEP measures could be re-evaluated. From the results of previous studies, behavioral performance would be expected to improve, however, it would be interesting to determine if AEP recordings are enhanced and if so, which aspects of the response are altered (i.e., latency and/or amplitude).

The suggestion that the behavioral responses measured in this study are indicative of a higher-level linguistic processing, where lexical, syntactic, and semantic knowledge mediate perception, are made with great caution due to the minimal linguistic properties of the stimuli used in this study. For future studies, it would be more prudent to use additional auditory evoked potential measures, such as the N400 and/or the P600, that occur primarily in response to those specific properties.
Conclusions

This study supports the assertion that speech is perceived differently than other acoustic stimuli. An attempt has been made to further the knowledge of how various types of acoustic stimuli are represented in the central auditory system and how they are transformed into meaningful signals by combining behavioral procedures and electrophysiologic measures.

In summary, the results of this study show enhanced discrimination to frequency-glides (non-speech) stimuli versus CV (speech) stimuli of analogous acoustical content. Behavioral responses exhibited greater abilities of detecting the non-speech, within-category stimulus contrast. MMN was present without regard to stimulus type. Also, P300 was present in the grand mean to non-speech, while absent to within-category speech. This study supports the assertion of Dalebout & Stack (1999) that several levels of processing (auditory, phonetic/phonemic, higher-order linguistic) mediate auditory perception of speech.
REFERENCES


APPENDICES
APPENDIX A

Participant Consent Form
Consent Form to Participate in the Following Project:
“A Comparison Between Behavioral Discrimination, MMN, and P300 Auditory Evoked Potentials to Speech and Nonspeech Stimuli”

You are being asked to participate in a study of the central auditory system’s speech processing abilities. You may be one of the twelve individuals chosen to participate in this study.

Criteria
To take part in this study, you must first consent to a hearing evaluation, which will be provided at no charge to you. The hearing evaluation will include a case history, test of hearing sensitivity, and tests of eardrum and ear canal health. If you do not pass all parts of the hearing exam you will be excluded from further participation.

Procedures
If you have none of the exclusionary criteria and agree to participate in the study you will be asked to listen to several syllables and label them as /ba/ or /da/. Then you will be scheduled for a 2-hour experimental session. During this session, you will hear several sets of two successive sounds (syllables and tones) presented via supra-aural headphones and will be asked to indicate if they sound the same or different by pushing a button. Then, surface electrodes will be placed on your head with electrode gel and medical tape and sounds will be presented to you via insert earphones. The electrodes will measure your auditory systems response to the sounds. During this time (approximately 1.5 hours) you will be seated comfortably in a sound-treated booth. At times you may be asked to ignore the tones or syllables and other times you will be asked to count the tones or syllables that are different. All the sounds will be presented at a comfortable loudness level. Completion of this experiment will take one two-hour session. You will be given frequent breaks if needed. You will be paid $10.00 per hour for a total of $20.00.

Potential risks or discomfort
There are no psychological, social, or legal risks associated with participation in this study.

Benefits
You will receive a free hearing evaluation, and monetary compensation at the rate of $10.00 per hour. The scientific and clinical communities will benefit from greater understanding of the perception abilities of the central auditory system.

Confidentiality
Any information obtained in this study will remain confidential and will be disclosed only with your permission. All information will be kept in a locked filing cabinet on the UT campus for 3 years and will then be destroyed.

Alternatives
You do not have to take part in this study if you do not want to. Your participation or non-participation in this project will in no way affect any future treatment or services you seek at the University of Tennessee, Department of Audiology and Speech Pathology at any time.

Right to withdraw
You can stop taking part in the study at any time, even after you sign this agreement. If you want to stop taking part in the study, simply tell us. There is no penalty for quitting. You will be paid for time served.

**Right to inquire**
If you have any questions about this study, you can write or call the researchers listed at the bottom of this form.

**Authorization**
I have read this form in its entirety and feel I understand the risks and benefits of this study. I agree to participate in this study. I acknowledge that I have received a copy of this consent form.

_________________________  ____________________
Participant’s signature     Date

**Investigator’s Assurance:**
The individuals whose names appear below are responsible for carrying out this research program. They assure that all questions about this research program are answered to the best of their abilities. They will assure that you are informed of any changes in the procedures or risks and benefits if any should occur during or after the course of this study. They assure that all information remains confidential.

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APPENDIX B

Case History Form
CASE HISTORY

Subject ID ____________  Sex ____________  Date ____________

Date of Birth ____________  Age ____________

1) Are you currently taking any over-the-counter or prescription medications? If so, which ones? For what? For how long?
__________________________________________________________

2) To your knowledge have you ever had any ear infections? If so when and how were they treated (e.g. antibiotics, surgery)?
__________________________________________________________

3) Is there any history of hearing loss in your family (mother, grandfather, sibling)?
__________________________________________________________

4) Have you ever sustained a head injury? If so, how and when?
__________________________________________________________

5) Have you ever been diagnosed with any cognitive, neurological, or learning deficits? If so, what?
__________________________________________________________
APPENDIX C

Example of Random Stimulus Presentation Among Trial Blocks
<table>
<thead>
<tr>
<th>Trial</th>
<th>Subject 1</th>
<th>Subject 2</th>
<th>Subject 3</th>
<th>Subject 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>P300 to CV</td>
<td>P300 to G</td>
<td>P300 to CV</td>
<td>P300 to CV</td>
</tr>
<tr>
<td>2</td>
<td>P300 to G</td>
<td>P300 to CV</td>
<td>P300 to G</td>
<td>P300 to CV</td>
</tr>
<tr>
<td>1</td>
<td>MMN to G</td>
<td>MMN to CV</td>
<td>MMN to CV</td>
<td>MMN to G</td>
</tr>
<tr>
<td>2</td>
<td>MMN to G</td>
<td>MMN to G</td>
<td>MMN to CV</td>
<td>MMN to CV</td>
</tr>
<tr>
<td>3</td>
<td>MMN to CV</td>
<td>MMN to G</td>
<td>MMN to G</td>
<td>MMN to CV</td>
</tr>
<tr>
<td>4</td>
<td>MMN to G</td>
<td>MMN to CV</td>
<td>MMN to G</td>
<td>MMN to CV</td>
</tr>
<tr>
<td>5</td>
<td>MMN to CV</td>
<td>MMN to G</td>
<td>MMN to G</td>
<td>MMN to CV</td>
</tr>
<tr>
<td>6</td>
<td>MMN to CV</td>
<td>MMN to G</td>
<td>MMN to G</td>
<td>MMN to CV</td>
</tr>
<tr>
<td>7</td>
<td>MMN to G</td>
<td>MMN to CV</td>
<td>MMN to G</td>
<td>MMN to CV</td>
</tr>
<tr>
<td>8</td>
<td>MMN to CV</td>
<td>MMN to G</td>
<td>MMN to G</td>
<td>MMN to CV</td>
</tr>
<tr>
<td>9</td>
<td>MMN to G</td>
<td>MMN to CV</td>
<td>MMN to G</td>
<td>MMN to CV</td>
</tr>
<tr>
<td>1</td>
<td>P300 to G</td>
<td>P300 to CV</td>
<td>P300 to G</td>
<td>P300 to CV</td>
</tr>
<tr>
<td>2</td>
<td>P300 to G</td>
<td>P300 to CV</td>
<td>P300 to G</td>
<td>P300 to CV</td>
</tr>
</tbody>
</table>

CV = Consonant-vowel speech stimuli
G = Frequency Glide non-speech stimuli
APPENDIX D

Individual Labeling Functions in Criterion Task
APPENDIX E

Individual MMN Waveforms
SUBJECT ONE: IPSILATERAL AND CONTRALATERAL MMN WAVEFORMS TO NON-SPEECH FREQUENCY GLIDES.

Standard & Deviant Waveforms: Thin lines represent response to standard stimuli and thick lines represent response to deviant stimuli.

Difference Waveforms: Measurements reported below.

- Onset (lpsi): 141.2 ms
- Offset (lpsi): 261.4 ms
- Duration (lpsi): 120.2 ms
- Mean Amplitude (lpsi): -0.06631
- Onset (contra): 141.2 ms
- Offset (contra): 261.4 ms
- Duration (contra): 120.2 ms
- Mean Amplitude (contra): -0.06908

Latency:
- lpsi: 171.2 ms
- contra: 177.7 ms
SUBJECT ONE: IPSILATERAL AND CONTRALATERAL MMN WAVEFORMS TO CV SPEECH.

Standard & Deviant Waveforms: Thin lines represent response to standard stimuli and thick lines represent response to deviant stimuli.

Difference Waveforms: Measurements reported below.

**S01 MMN Speech (Ipsi)**

- Onset: 98.2 ms
- Offset: 340.9 ms
- Duration: 242.7 ms
- Latency: 220.6 ms
- Mean Amplitude: -0.01492

**S01 MMN Speech (Contra)**

- Onset: 98.2 ms
- Offset: 340.9 ms
- Duration: 242.7 ms
- Latency: 224.9 ms
- Mean Amplitude: -0.01942
SUBJECT TWO: IPSILATERAL AND CONTRALATERAL MMN WAVEFORMS TO NON-SPEECH FREQUENCY GLIDES.

Standard & Deviant Waveforms: Thin lines represent response to standard stimuli and thick lines represent response to deviant stimuli.

Difference Waveforms: Measurements reported below.

- S02 MMN Glides (Ipsi) Difference Wave
  - Onset=141.2ms
  - Offset=261.4ms
  - Duration=120.2ms
  - Latency=240ms
  - Mean Amplitude=-0.4338

- S02 MMN Glides (Contra) Difference Wave
  - Onset=141.2ms
  - Offset=261.4ms
  - Duration=120.2ms
  - Latency=237.8ms
  - Mean Amplitude= -0.04184
SUBJECT TWO: IPSILATERAL AND CONTRALATERAL MMN WAVEFORMS TO CV SPEECH.

Standard & Deviant Waveforms: Thin lines represent response to standard stimuli and thick lines represent response to deviant stimuli.

Difference Waveforms: Measurements reported below.
Onset= 98.2 ms  
Offset=340.9 ms  
Latency= 247.3 ms  
Duration=242.7 ms  
Mean Amplitude= 0.005502
SUBJECT THREE: IPSILATERAL AND CONTRALATERAL MMN WAVEFORMS TO NON-SPEECH FREQUENCY GLIDES.

S03 MMN Glides (Ipsi)

S03 MMN Glides (Contra)

Standard & Deviant Waveforms: Thin lines represent response to standard stimuli and thick lines represent response to deviant stimuli.

S03 MMN Glides (Ipsi) Difference Wave

S03 MMN Glides (Contra) Difference Wave

Difference Waveforms: Measurements reported below.

Onset=141.2ms
Offset=261.4ms
Duration=120.2ms
Avg Amplitude=-0.0332

Onset=141.2ms
Offset=261.4ms
Duration=120.2ms
Latency=214.2ms
Avg Amplitude=-0.01247
SUBJECT THREE: IPSILATERAL AND CONTRALATERAL MMN WAVEFORMS TO CV SPEECH.

Standard & Deviant Waveforms: Thin lines represent response to standard stimuli and thick lines represent response to deviant stimuli.

Difference Waveforms: Measurements reported below.

<table>
<thead>
<tr>
<th></th>
<th>Onset</th>
<th>Offset</th>
<th>Latency</th>
<th>Duration</th>
<th>Mean Amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>S03 MMN Speech (Ipsi) Difference Wave</td>
<td>98.2ms</td>
<td>340.9ms</td>
<td>252.8ms</td>
<td>242.7ms</td>
<td>-0.0070924</td>
</tr>
<tr>
<td>S03 MMN Speech (Contra) Difference Wave</td>
<td>98.2ms</td>
<td>340.9ms</td>
<td></td>
<td>242.7ms</td>
<td>-0.00958</td>
</tr>
</tbody>
</table>
SUBJECT FOUR: IPSILATERAL AND CONTRALATERAL MMN WAVEFORMS TO NON-SPEECH FREQUENCY GLIDES.

Standard & Deviant Waveforms: Thin lines represent response to standard stimuli and thick lines represent response to deviant stimuli.

Difference Waveforms: Measurements reported below.

- **Onset**: 141.2 ms
- **Offset**: 261.4 ms
- **Duration**: 120.2 ms
- **Latency**: 227.1 ms
- **Mean Amplitude**: -0.06121
- **Peak**: 222.8 ms @ -1335
- **Area**: 16.99126
- **AVG Amplitude**: -0.04225
SUBJECT FOUR: IPSILATERAL AND CONTRALATERAL MMN WAVEFORMS TO CV SPEECH.

Standard & Deviant Waveforms: Thin lines represent response to standard stimuli and thick lines represent response to deviant stimuli.

Difference Waveforms: Measurements reported below:

- Onset= 98.2ms
- Offset=340.9ms
- Latency=143.3ms
- Duration= 242.7 ms
- Mean Amplitude= 0.016673

- Onset= 98.2ms
- Offset=340.9ms
- Latency= 143.3ms
- Duration= 242.7 ms
- Mean Amplitude= 0.021041
SUBJECT FIVE: IPSILATERAL AND CONTRALATERAL MMN WAVES TO NON-SPEECH FREQUENCY GLIDES.

Standard & Deviant Waveforms: Thin lines represent response to standard stimuli and thick lines represent response to deviant stimuli.

Difference Waveforms: Measurements reported below.
- Onset=141.2ms
- Offset=261.4ms
- Duration=120.2ms
- Latency=226.1ms
- Mean Amplitude=0.001312
SUBJECT FIVE: IPSILATERAL AND CONTRALATERAL MMN WAVES TO CV SPEECH.

Standard & Deviant Waveforms: Thin lines represent response to standard stimuli and thick lines represent response to deviant stimuli.

Difference Waveforms: Measurements reported below.

Onset = 98.2 ms
Offset = 340.9 ms
Latency = 162.6 ms
Duration = 242.7 ms
Mean Amplitude = 0.002993

Onset = 98.2 ms
Offset = 340.9 ms
Latency = 141.2 ms
Duration = 242.7 ms
Mean Amplitude = -0.0083
SUBJECT SIX: IPSILATERAL AND CONTRALATERAL MMN WAVEFORMS TO NON-SPEECH FREQUENCY GLIDES.

Standard & Deviant Waveform: Thin lines represent response to standard stimuli and thick lines represent response to deviant stimuli.

Difference Waveforms: Measurements reported below.

Onset=141.2ms
Offset=261.4ms
Duration=120.2ms
Mean Amplitude=-0.04079

Onset=141.2ms
Offset=261.4ms
Duration=120.2ms
Mean Amplitude=-0.03591
SUBJECT SIX: IPSILATERAL AND CONTRALATERAL MMN WAVEFORMS TO CV SPEECH.

Standard & Deviant Waveform: Thin lines represent response to standard stimuli and thick lines represent response to deviant stimuli.

Difference Waveforms: Measurements reported below:

- **Onset** = 98.2 ms
- **Offset** = 340.9 ms
- **Duration** = 242.7 ms
- **Latency** = 162.6 ms
- **Mean Amplitude** = -0.02145

- **Onset** = 98.2 ms
- **Offset** = 340.9 ms
- **Duration** = 242.7 ms
- **Latency** = 224.9 ms
- **Mean Amplitude** = -0.00813
SUBJECT SEVEN: IPSILATERAL AND CONTRALATERAL MMN WAVEFORMS TO NON-SPEECH FREQUENCY GLIDES.

Standard & Deviant Waveforms: Thin lines represent response to standard stimuli and thick lines represent response to deviant stimuli.

Difference Waveforms: Measurements reported below:

S07 MMN Glides (Ipsi)

Difference Wave

S07 MMN Glides (Contra)

Difference Wave

Onset=141.2 ms
Offset=261.4 ms
Latency=227.1 ms
Duration=120.2 ms
Mean Amplitude=-0.02961

Onset=141.2 ms
Offset=261.4 ms
Latency=188.4 ms
Duration=120.2 ms
Mean Amplitude=-0.01579
SUBJECT SEVEN: IPSILATERAL AND CONTRALATERAL MMN WAVEFORMS TO CV SPEECH.

Standard & Deviant Waveforms: Thin lines represent response to standard stimuli and thick lines represent response to deviant stimuli.

Difference Waveforms: Measurements reported below:

- Onset: 98.2ms
- Offset: 340.9ms
- Latency: 278.6ms
- Duration: 242.7ms
- Mean Amplitude: -0.01191

- Onset: 98.2ms
- Offset: 340.9ms
- Latency: 276.5ms
- Duration: 242.7ms
- Mean Amplitude: -0.02013
SUBJECT EIGHT: IPSILATERAL AND CONTRALATERAL MMN WAVEFORMS TO NON-SPEECH FREQUENCY GLIDES.

Standard & Deviant Waveforms: Thin lines represent response to standard stimuli and thick lines represent response to deviant stimuli.

Difference Waveforms: Measurements reported below.

- Ipsilateral MMN Glides:
  - Onset: 141.2ms
  - Offset: 261.4ms
  - Duration: 120.2ms
  - Latency: 214.2ms
  - Mean amplitude: 0.017624

- Contralateral MMN Glides:
  - Onset: 141.2ms
  - Offset: 261.4ms
  - Duration: 120.2ms
  - Latency: 199.1ms
  - Mean Amplitude: 0.017457
SUBJECT EIGHT: IPSILATERAL AND CONTRALATERAL MMN WAVEFORMS TO CV SPEECH.

Standard & Deviant Waveforms: Thin lines represent response to standard stimuli and thick lines represent response to deviant stimuli.

Difference Waveforms: Measurements reported below.

Onset = 98.2ms
Offset = 340.9ms
Duration = 242.7 ms
Mean Amplitude = -0.00343

Onset = 98.2ms
Offset = 340.9ms
Duration = 242.7 ms
Mean Amplitude = -0.00343
SUBJECT NINE: IPSILATERAL AND CONTRALATERAL MMN WAVEFORMS TO NON-SPEECH FREQUENCY GLIDES.

Standard & Deviant Waveforms: Thin lines represent response to standard stimuli and thick lines represent response to deviant stimuli.

Difference Waveforms: Measurements reported below.

- **S09 MMN Glides (Ipsi)**
  - Onset=141.2ms
  - Offset=261.4ms
  - Duration=120.2ms
  - Latency = 227.1 ms
  - Mean Amplitude = -0.04181

- **S09 MMN Glides (Contra)**
  - Onset=141.2ms
  - Offset=261.4ms
  - Duration=120.2ms
  - Latency = 231.4ms
  - Mean Amplitude = -0.03113
SUBJECT NINE: IPSILATERAL AND CONTRALATERAL MMN WAVEFORMS TO CV SPEECH.

Standard & Deviant Waveforms: Thin lines represent response to standard stimuli and thick lines represent response to deviant stimuli.

Difference Waveforms: Measurements reported below.

- S09 MMN Speech (lpsi)
  - Onset=98.2ms
  - Offset=340.9ms
  - Duration=242.7ms
  - Latency=124ms
  - Mean Amplitude=-0.01638

- S09 MMN Speech (Contra)
  - Onset=98.2ms
  - Offset=340.9ms
  - Duration=242.7ms
  - Latency=124ms
  - Mean Amplitude=-0.00861
SUBJECT TEN: IPSILATERAL AND CONTRALATERAL MMN WAVEFORMS TO NON-SPEECH FREQUENCY GLIDES.

Standard & Deviant Waveforms: Thin lines represent response to standard stimuli and thick lines represent response to deviant stimuli.

Difference Waveforms: Measurements reported below.

S10 MMN Glides (Ipsi)

Amplitude (microV)

Time (ms)

Onset=141.2ms
Offset=261.4ms
Duration=120.2ms

Mean Amplitude= -0.0208

S10 MMN Glides (Contra)

Amplitude (microV)

Time (ms)

Onset=141.2ms
Offset=261.4ms
Duration=120.2ms

Latency=197 ms
Mean Amplitude= -0.02007
SUBJECT TEN: IPSILATERAL AND CONTRALATERAL MMN WAVEFORMS TO CV SPEECH.

Standard & Deviant Waveforms: Thin lines represent response to standard stimuli and thick lines represent response to deviant stimuli.

Difference Waveforms: Measurements reported below.

Onset= 98.2ms
Offset= 340.9ms
Duration= 242.7ms
Mean Amplitude= 0.003589
APPENDIX F

Individual P300 Waveforms
SUBJECT ONE: IPSILATERAL AND CONTRALATERAL P300 WAVEFORMS TO NON-SPEECH FREQUENCY GLIDES.

Standard & Deviant Waveforms: Thin lines represent response to standard stimuli and thick lines represent response to deviant stimuli.

Difference Waveforms: Measurements reported below.

Onset = 216.3ms  Latency= 276.5ms
Offset=409.6ms  P-P amp= 0.7884
Duration= 193.3ms  Mean Amplitude= -0.01515

Onset = 216.3ms  Latency=298ms
Offset=409.6ms  P-P amp= 0.693267
Duration= 193.3ms  Mean Amplitude= -0.00201
SUBJECT ONE: IPSILATERAL AND CONTRALATERAL P300 WAVEFORMS TO CV SPEECH.

S01 P300 Speech (lpsi)

S01 P300 Speech (Contra)

Standard & Deviant Waveforms: Thin lines represent response to standard stimuli and thick lines represent response to deviant stimuli.

SO1 P300 Speech (lpsi) Difference Wave

SO1 P300 Speech (Contra) Difference Wave

Difference Waveforms: Measurements reported below.

Onset=250.7ms  Latency= 398.9ms
Offset=450.4ms  P-P amplitude= 0.2922
Duration= 199.7ms  Mean Amplitude= -0.0142

Onset=250.7ms  Latency= 386ms
Offset=450.4ms  P-P amplitude= 0.243
Duration= 199.7ms  Mean Amplitude= -0.044
SUBJECT TWO: IPSILATERAL AND CONTRALATERAL P300 WAVEFORMS TO NON-SPEECH FREQUENCY GLIDES.

Standard & Deviant Waveforms: Thin lines represent response to standard stimuli and thick lines represent response to deviant stimuli.

Difference Waveforms: Measurements reported below.

- **S02 P300 Gildes (ipsi)**
  - Onset= 216.3ms
  - Offset= 409.6ms
  - Duration= 193.3ms
  - Latency=366ms
  - P-P amplitude= 0.23533
  - Mean Amplitude=0.017038

- **S02 P300 Gildes (Contra)**
  - Onset= 216.3ms
  - Offset= 409.6ms
  - Duration= 193.3ms
  - Latency=390.3ms
  - P-P amplitude= 0.248667
  - Mean Amplitude= 0.032457
SUBJECT TWO: IPSILATERAL AND CONTRALATERAL P300 WAVEFORMS TO CV SPEECH.

Standard & Deviant Waveforms: Thin lines represent response to standard stimuli and thick lines represent response to deviant stimuli.

Difference Waveforms: Measurements reported below.

**S02 P300 Speech (lpsi) Difference Wave**
- Onset = 25.7 ms
- Latency = 436.7 ms
- Offset = 450.4 ms
- P-P amplitude = 0.3464
- Duration = 199.7 ms
- Mean Amplitude = 0.03468

**S02 P300 Speech (Contra) Difference Wave**
- Onset = 250.7 ms
- Latency = 437.6 ms
- Offset = 450.4 ms
- P-P amplitude = 0.3633
- Duration = 199.7 ms
- Mean Amplitude = 0.003822
SUBJECT THREE: IPSILATERAL AND CONTRALATERAL P300 WAVEFORMS TO NON-SPEECH FREQUENCY GLIDES.

**Standard & Deviant Waveforms:** Thin lines represent response to standard stimuli and thick lines represent response to deviant stimuli.

**Difference Waveforms:** Measurements reported below.

- **Ipsilateral:**
  - Onset: 216.3ms
  - Offset: 409.6ms
  - Duration: 193.3ms
  - P-P amplitude: 0.7268
  - Latency: 287.2ms
  - Mean Amplitude: 0.087393

- **Contralateral:**
  - Onset: 216.3ms
  - Offset: 409.6ms
  - Duration: 193.3ms
  - P-P amplitude: 0.6956
  - Latency: 287.2ms
  - Mean Amplitude: 0.07268
SUBJECT THREE: IPSILATERAL AND CONTRALATERAL P300 WAVEFORMS TO CV SPEECH.

Difference Waveforms: Measurements reported below.

**Ipsilateral Waveforms:**
- **Onset:** 250.7 ms
- **Latency:** 381.7 ms
- **Offset:** 450.4 ms
- **P-P amplitude:** 0.396033
- **Duration:** 199.7 ms
- **Mean Amplitude:** 0.070536

**Contralateral Waveforms:**
- **Onset:** 250.7 ms
- **Latency:** 377.4 ms
- **Offset:** 450.4 ms
- **P-P amplitude:** 0.451733
- **Duration:** 199.7 ms
- **Avg amplitude:** 0.069773

Standard & Deviant Waveforms: Thin lines represent response to standard stimuli and thick lines represent response to deviant stimuli.
SUBJECT FOUR: IPSILATERAL AND CONTRALATERAL P300 WAVEFORMS TO NON-SPEECH FREQUENCY GLIDES.

Standard & Deviant Waveforms: Thin lines represent response to standard stimuli and thick lines represent response to deviant stimuli.

Difference Waveforms: Measurements reported below.

Onset= 216.3ms
Offset= 409.6ms
Duration= 193.3ms
P-P amplitude= 0.669967
Mean Amplitude= 0.039464

Onset= 216.3ms
Offset= 409.6ms
Duration= 193.3ms
P-P amplitude= 0.5396
Mean Amp= 0.025869
SUBJECT FOUR: IPSILATERAL AND CONTRALATERAL P300 WAVEFORMS TO CV SPEECH.

Standard & Deviant Waveforms: Thin lines represent response to standard stimuli and thick lines represent response to deviant stimuli.

Difference Waveforms: Measurements reported below.

**Ipsilateral (Lpsi):**
- Onset: 250.7ms
- Latency: 422.5ms
- Offset: 450.4ms
- P-P amplitude: 0.276
- Duration: 199.7ms
- Mean amplitude: 0.1912

**Contralateral (Contra):**
- Onset: 250.7ms
- Latency: 420.4ms
- Offset: 450.4ms
- P-P amplitude: 0.276
- Duration: 199.7ms
- Mean amplitude: 0.02532
SUBJECT FIVE: IPSILATERAL AND CONTRALATERAL P300 WAVES TO NON-SPEECH FREQUENCY GLIDES.

Standard & Deviant Waveforms: Thin lines represent response to standard stimuli and thick lines represent response to deviant stimuli.

Difference Waveforms: Measurements reported below.

S05 P300 Glides (Ipsi) Difference Wave

- Onset = 216.3ms
- Offset = 409.6ms
- Duration = 193.3ms
- Latency = 308.7ms
- P-P amplitude = 0.3619
- Mean Amplitude = -0.103

S05 P300 Glides (Contra) Difference Wave

- Onset = 216.3ms
- Offset = 409.6ms
- Duration = 193.3ms
- Latency = 390.3ms
- P-P amplitude = 0.1172
- Mean Amplitude = -0.1265
SUBJECT FIVE: IPSILATERAL AND CONTRALATERAL P300 WAVES TO CV SPEECH.

Standard & Deviant Waveforms: Thin lines represent response to standard stimuli and thick lines represent response to deviant stimuli.

Difference Waveforms: Measurements reported below.

Onset= 250.7ms
Offset= 450.7ms
Duration= 199.7ms
Mean Amplitude= -0.00033

Onset= 250.7ms
Offset= 450.7ms
Duration= 199.7ms
Mean Amplitude= -0.0218

Latency= 295.8ms
P-P amplitude= 0.2272

Latency= 353.8ms
P-P amplitude= 0.1927
SUBJECT SIX: IPSILATERAL AND CONTRALATERAL P300 WAVEFORMS TO NON-SPEECH FREQUENCY GLIDES.

Standard & Deviant Waveforms: Thin lines represent response to standard stimuli and thick lines represent response to deviant stimuli.

Difference Waveforms: Measurements reported below.

S06 P300 Glides (ipsi)  
Difference Wave  

-50 -2.7 44.5 91.8 139 186.3 233.5 280.8 328 375.3 422.5 469.8 Time (ms)

Onset= 216.3ms  
Offset=409.6ms  
Duration=193.3ms  
P-P amplitude= 1.387  
Mean Amplitude= 0.141443

S06 P300 Glides (Contra)  
Difference Wave  

-50 -2.7 44.5 91.8 139 186.3 233.5 280.8 328 375.3 422.5 469.8 Time (ms)

Onset= 216.3ms  
Offset=409.6ms  
Duration=193.3ms  
P-P amplitude= 1.4686  
Mean Amplitude= 0.1249
SUBJECT SIX: IPSILATERAL AND CONTRALATERAL P300 WAVEFORMS TO CV SPEECH.

**S06 P300 Speech (lpsi)**

- Onset = 250.7ms
- Latency = 325.9ms
- Offset = 450.4ms
- P-P amplitude = 0.4034
- Duration = 199.7ms
- Mean amplitude = 0.0179

**S06 P300 Speech (Contra)**

- Onset = 250.7ms
- Latency = 336.5ms
- Offset = 450.4ms
- P-P amplitude = 0.5188
- Duration = 199.7ms
- Mean Amplitude = 0.0161

Standard & Deviant Waveforms: Thin lines represent response to standard stimuli and thick lines represent response to deviant stimuli.

Difference Waveforms: Measurements reported below.
SUBJECT SEVEN: IPSILATERAL AND CONTRALATERAL P300 WAVEFORMS TO NON-SPEECH FREQUENCY GLIDES.

Standard & Deviant Waveforms: Thin lines represent response to standard stimuli and thick lines represent response to deviant stimuli.

Difference Waveforms: Measurements reported below:

- **Onset** = 216.3 ms
- **Latency** = 340.9 ms
- **Offset** = 409.6 ms
- **P-P amplitude** = 0.24
- **Duration** = 193.3 ms
- **Mean Amplitude** = 0.0449

- **Onset** = 216.3 ms
- **Latency** = 338.8 ms
- **Offset** = 409.6 ms
- **P-P amplitude** = 0.3536
- **Duration** = 193.3 ms
- **Mean Amplitude** = 0.07652
SUBJECT SEVEN: IPSILATERAL AND CONTRALATERAL P300 WAVEFORMS TO CV SPEECH.

Standard & Deviant Waveforms: Thin lines represent response to standard stimuli and thick lines represent response to deviant stimuli.

Difference Waveforms: Measurements reported below:

Onset=250.7ms  Latency= 310.8ms
Offset=450.4ms  P-P amplitude= 0.2561
Duration= 199.7ms  Mean amplitude= 0.009493

Onset=250.7ms  Latency= 328 ms
Offset=450.4ms  P-P amplitude= 0.2445
Duration= 199.7ms  Mean amplitude= -0.02672
SUBJECT EIGHT: IPSILATERAL AND CONTRALATERAL P300 WAVEFORMS TO NON-SPEECH FREQUENCY GLIDES.

Standard & Deviant Waveforms: Thin lines represent response to standard stimuli and thick lines represent response to deviant stimuli.

Difference Waveforms: Measurements reported below.

**S08 P300 Glides (Ipsi)**

- Onset: 216.3ms
- Offset: 409.6ms
- Duration: 193.3ms
- Latency: 289.4ms
- Mean Amplitude: 0.02353
- P-P Amplitude: 0.390433

**S08 P300 Glides (Contra)**

- Onset: 216.3ms
- Offset: 409.6ms
- Duration: 193.3ms
- Latency: 267.9ms
- Mean Amplitude: 0.039562
- P-P Amplitude: 0.484967
SUBJECT EIGHT: IPSILATERAL AND CONTRALATERAL P300 WAVEFORMS TO CV SPEECH.

Standard & Deviant Waveforms: Thin lines represent response to standard stimuli and thick lines represent response to deviant stimuli.

Difference Waveforms: Measurements reported below.

- S08 P300 Speech (lpsi)
  - Onset=250.7ms
  - Offset=450.7ms
  - Duration=199.7ms

- S08 P300 Speech (Contra)
  - Onset=250.7ms
  - Offset=450.7ms
  - Duration=199.7ms

- JR P300 Speech Ch 2
  - Latency= 431.1ms
  - P-P amplitude= 0.469
  - Mean amplitude= 0.0897
SUBJECT NINE: IPSILATERAL AND CONTRALATERAL P300 WAVEFORMS TO NON-SPEECH FREQUENCY GLIDES.

**S09 P300 Glides (ipsi)**

Time (ms): -50, -2.7, 44.5, 91.8, 139, 186.3, 233.5, 280.8, 328, 375.3, 422.5, 469.8

**S09 P300 Glides (Contra)**

Time (ms): -50, -2.7, 44.5, 91.8, 139, 186.3, 233.5, 280.8, 328, 375.3, 422.5, 469.8

Standard & Deviant Waveforms: Thin lines represent response to standard stimuli and thick lines represent response to deviant stimuli.

**Difference Waveforms:** Measurements reported below.

**S09 P300 Glides (ipsi) Difference Wave**

- Onset: 216.3ms
- Offset: 409.6ms
- Duration: 193.3ms
- Latency: 323.7ms
- P-P amplitude: 0.3852
- Mean Amplitude: 0.05434

**S09 P300 Glides (Contra) Difference Wave**

- Onset: 216.3ms
- Offset: 409.6ms
- Duration: 193.3ms
- Latency: 306.5ms
- P-P amplitude: 0.171
- Mean Amplitude: 0.000884
SUBJECT NINE: IPSILATERAL AND CONTRALATERAL P300 WAVEFORMS TO CV SPEECH.

Standard & Deviant Waveforms: Thin lines represent response to standard stimuli and thick lines represent response to deviant stimuli.

Difference Waveforms: Measurements reported below.

<table>
<thead>
<tr>
<th></th>
<th>Ipsilateral</th>
<th>Contralateral</th>
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</thead>
<tbody>
<tr>
<td>Onset</td>
<td>250.7ms</td>
<td>250.7ms</td>
</tr>
<tr>
<td>Offset</td>
<td>450.4ms</td>
<td>450.4ms</td>
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<tr>
<td>Duration</td>
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<td>199.7ms</td>
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<tr>
<td>Latency</td>
<td>398.9ms</td>
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<td>P-P amplitude</td>
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<td>Mean amplitude</td>
<td>0.0988</td>
<td>0.0736</td>
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</tbody>
</table>
SUBJECT TEN: IPSILATERAL AND CONTRALATERAL P300 WAVEFORMS TO NON-SPEECH FREQUENCY GLIDES.

Standard & Deviant Waveforms: Thin lines represent response to standard stimuli and thick lines represent response to deviant stimuli.

Difference Waveforms: Measurements reported below.

- **S10 P300 Glides (Ipsi)**
  - Onset=216.3ms
  - Latency= 276.5ms
  - Offset=409.6ms
  - P-P amplitude=.124
  - Duration= 193.3ms
  - Mean Amplitude=-0.00077

- **S10 P300 Glides (Contra)**
  - Onset=216.3ms
  - Latency= 276.5ms
  - Offset=409.6ms
  - P-P amplitude=.1129
  - Duration= 193.3ms
  - Mean Amplitude=-0.1032
SUBJECT TEN: IPSILATERAL AND CONTRALATERAL P300 WAVEFORMS TO CV SPEECH.

Standard & Deviant Waveforms: Thin lines represent response to standard stimuli and thick lines represent response to deviant stimuli.

Difference Waveforms: Measurements reported below.

S10 P300 Speech (Ipsi)  
Difference Wave  
onset= 250.7ms  
Latency= 304.4  
offset= 450.4ms  
P-P-Amplitude= 0.2395  
duration= 199.7ms  
Mean amplitude= 0.03395

S10 P300 Speech (Contra)  
Difference Wave  
onset= 250.7ms  
Latency= 298ms  
offset= 450.4ms  
P-P-Amplitude= 0.3314  
duration= 199.7ms  
Mean Amplitude= 0.0384
Vita

Joanna Dee Webster was born in Knoxville, Tennessee on October 13, 1975. She attended elementary and secondary schools in the Jefferson County School System. After graduating High School in 1993, she received a Bachelor of Science degree in Biology with a minor in Philosophy, from the University of Tennessee, Knoxville in 1997. Joanna continued her education at U.T., receiving her master’s degree in Audiology in May of 2002.