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Changes in the Perception of Stop Consonants Through Enhanced Cue Training as Reflected by Categorical Boundaries and Late Auditory Evoked Potentials

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To the Graduate Council:

I am submitting herewith a dissertation written by Clifford Anthony Franklin entitled "Changes in the Perception of Stop Consonants Through Enhanced Cue Training as Reflected by Categorical Boundaries and Late Auditory Evoked Potentials." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Speech and Hearing Science.

Ashley W. Harkrider, Major Professor

We have read this dissertation and recommend its acceptance:

Mark Hedrick, James Thelin, Jimmie Cree Hall

Accepted for the Council:

Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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recommend its acceptance:

Mark Hedrick

James Thelin

Jimmie Cree Hall

Acceptance for the Council:

Anne Mayhew

Vice Chancellor and Dean of Graduate
Studies

(Original signatures are on file with official student records.)

CHANGES IN THE PERCEPTION OF STOP CONSONANTS THROUGH ENHANCED CUE TRAINING AS REFLECTED BY CATEGORICAL BOUNDARIES AND LATE AUDITORY EVOKED POTENTIALS

A Dissertation
Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

Clifford Anthony Franklin
May, 2004

Dedication

This dissertation is dedicated to my loving wife, Jennifer and my father, the late Clifford Franklin, Sr. and my mother, Jean Franklin, and my brothers, Clay, Jim and Alan, and my sister Kate, and the rest of my family, for always challenging and encouraging me to achieve more than I ever thought possible.

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Abstract

Hearing-impaired listeners have difficulty in discriminating between voiced stop consonants. An important acoustic cue in this discrimination is the transition from the frequency of the consonant to the frequency of the vowel. The main purpose of this study was to investigate the effect of auditory training on the perception of the formant transition cue in the discrimination of the place of articulation of voiced stop consonants in synthetic CV stimuli of hearing-impaired listeners. Changes in perception were represented by behavioral and electrophysiological measures. Generalization effects after training and correlations between behavioral and electrophysiological measures were also measured.

Eight male and three female hearing-impaired subjects (23 - 72 years of age) participated in this study. The behavioral measures involved the participants performing categorization of stimuli as either /b/ and /d/ in a 2AFC task. Stimuli varied in onset frequency of the second formant. Electrophysiological measures, including P100, N100, P200, N200 latencies and P100-N100, N100-P200, P200-N200 peak-to-peak amplitudes, were recorded as participants sat quietly while watching a video in silence as stimuli was presented in one ear.

Subjects participated in auditory training on the formant transition cue over the period of four days. Stimuli used in auditory training were consistent with stimuli used in behavioral and electrophysiological measures, except that the formant transition cue was enhanced during training. This enhancement resulted from amplification of the transition portion of the stimulus to ensure audibility of the cue for the listener. Behavioral measures involved identifying the category (/b/ or /d/) to which the stimulus belonged. Visual feedback was given after each correct response.

Results were consistent with previous studies. Behavioral measures indicated improvement from before training to after training in the perception of the formant transition cue by some listeners. However, analysis of variance (ANOVA) and correlation procedures failed to reflect any pre versus post training change. Age and severity of hearing were not correlated with improvement due to training. However, ability to categorize prior to training correlated with improvement after training. Statistical results for electrophysiological measures did not find significant changes between pre and post training.

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CHAPTER I
Introduction

Many hearing-impaired individuals have difficulty understanding speech. One specific speech sound, the stop consonant, is known to be difficult for hearing-impaired listeners to understand. One of the acoustic cues used in the discrimination between stop consonants is the formant transition cue. The formant transition cue is a change between the frequency of the consonant and the frequency of the vowel following the consonant. The formant transition cue is key in the perception of the place of articulation of stop consonants for normal hearing listeners (Delattre, et al., 1955). Hearing-impaired listeners have more difficulty with the perception of the formant transition and do not rely on it as much as normal-hearing listeners (Hedrick et al., 1995).

Although difficulty in using the formant transition cue is a problem for hearing-impaired listeners, improved perceptions of this cue may occur with auditory training. Training has been shown to improve frequency discrimination and speech-sound perception abilities (Demany and Semal, 2002; Irvine, Martin, Klimkeit, and Smith, 2000). If hearing impaired listeners can learn to improve the use of this cue, their speech perception may also improve. Speech cues can be enhanced through amplification of the cue, lengthening of the cue, or other modifications to the cue within the speech signal (Revoile, Holden-Pitt, Edward, Pickett and Brandt, 1987; Revoile, Holden-Pitt, Edward, and Pickett, 1986; Revoile, Holden-Pitt, Pickett and Brandt, 1986). Enhancement of speech cues improves perception of speech sounds for hearing-impaired individuals and is also useful in auditory training (Revoile et al., 1987). Auditory training using enhanced cues may result in increased likelihood of successful training of the formant transition cue.

To determine if any change in the use of the formant transition cue has occurred, two types of measurement have been used. The tools used in the assessment of speech-sound perception included behavioral and electrophysiological measures. While behavioral measures have established the basis for speech perception research, these measures require subject participation and possible testing biases (for review see Green and Swets, 1988, Macmillian and Creelman, 1991). Electrophysiological measures are relatively new in the role of measuring speech perception. Electrophysiological measures require only passive participation by the listener, allowing for objective measurements reflecting neural auditory processing (for review see McPherson, 1996).

CHAPTER II
Literature Review

Assessment of Discrimination

Behavioral Responses. Measurements of a listener's sensitivity to the existence of a signal or changes in a signal by controlling for the listener's decision criteria reflect how sensory processes vary with stimulus changes. Inferences can be drawn on the type and amount of sensory information used by the observer. These inferences give insight into the nature of sensory processing (for review see Green and Swets, 1988, Macmillian and Creelman,1991). Two important values in such assessments include a detectability index (d') and the proportion of correct responses (P(c)). According to Macmillian and Creelman, d' is the most valuable sensitivity measure. It is defined in terms of z-scores transformed from the percentage of correct responses, known as "hits" and the percentage of false-positive responses, known as "false-alarms". The value of d' is equal to the z-score for hits minus the z-score for false-alarms. In cases where the probability of obtaining a false positive is very low, P(c) is used as an estimate of d'. Both d' and P(c) are used to measure a listener's ability to discriminate between two similar sounds.

Another method of measuring discrimination is categorization. Categorization or categorical perception is a form of gross discrimination. The discrimination is based on the listener's ability to identify which category a speech sound belongs. Categories are divided by boundaries. An example of this phenomenon involves the perception of the sounds /b/ and /d/. For instance, the value of an acoustic cue used in the perception of /b/

varies along an array of incrementally divided values or a continuum towards the value of that same cue used in the perception of /d/. At a point along this change, the perception moves abruptly towards the perception of /d/ and continues that direction in a gradual manner. The point at which the perception has a fifty percent chance of being identified as a /b/ or a /d/ is known as the listener's categorical boundary for that sound or cue (for review see Borden, Harris, and Raphael, 1994).

Measurements of d', and P(c) are commonly used to determine differential thresholds or the smallest change in a stimulus that is detectable. It is through these measures that we observe the skills that enable a listener to distinguish a simple tone from another, a complex signal from another or one speech sound from another. Changes in discrimination due to training can be measured using d', P(c), and characteristics of the psychometric function (e.g. slope). These measures are also useful in measuring any generalization of training from one stimulus to another.

Electrophysiological Responses. Processing of auditory stimuli in the central auditory nervous system (CANS) is reflected in electrophysiological measures of auditory evoked potentials. Long latency auditory evoked potentials typically consist of a series of positive and negative peaks within a time window ranging from 50 ms to 500 ms following the onset of the stimulus eliciting the responses. The first peak in the series is a positive peak at about 50-80 ms and is referred to as P100. The P100 response may be considered part of the long latency auditory evoked potentials or the middle latency auditory evoked response, depending on the stimulus repetition rate and recording window (Kraus et al., 1993). This may be the reason why the P100 response is not frequently used in investigations of auditory processing at the cortical level. Following the P100 response is a negative peak at about 80-150 ms latency, known as the N100 response. The N100 response, in turn, is followed by another positive peak, referred to as the P200 response. The P200 response typically ranges from 145-180 ms. These responses are commonly used in research and according to Kraus et al., are considered to be ubiquitous. The P200 response is trailed by a second negative peak called the N200 response at 180-250 ms. Event-related potentials such as mismatched negativity (MMN) and the P300 response are also electrophysiological measures that reflect the processing of auditory stimuli in the CANS. MMN is a small negative deflection in the latency range of the P200 wave. A positive peak, referred to as P300, can be recorded in the time range of 220-380 ms when the listener consciously detects a change in the stimuli. Both MMN and the P300 differ from other late auditory evoked potentials in that they require a change in the stimulus (for review see McPherson, 1996).

The N100 response is an exogenous response to the presentation of a series of homogeneous stimuli, meaning that it is signal driven as opposed to event-related. It is a product of several simultaneously active neuronal generators. The N100 receives contributions from auditory cortex, the lateral temporal lobe, and possibly the frontal lobe. The N100 can be elicited by a change in frequency of a continuous stimulus. However, N100 is typically elicited from short duration stimuli that are separated from each other by silent intervals. The N100 can be elicited regardless of the amount of attention given to the stimulus by the listener, but will show an increase in amplitude with attention to the stimulus. While the N100 amplitude varies among subjects, the N100 amplitude decreases and the N100 latency increases as the intensity of the stimulus decreases. The N100 amplitude will continue to increase for some subjects at high stimulus intensity levels and may level off or decrease in amplitude for other subjects (for review see Naatanen and Picton, 1987; Hyde, 1997; Naatanen and Winkler, 1999).

The N100 response is affected by hearing impairment. The N100 amplitude decreases and the latency increases with increased hearing loss or masking that simulates hearing loss (for review see Stapells, 2002). The N100 response is affected by small changes in a speech signal. The N100 elicited by a plosive-vowel combination (i.e. /da/, /pa/, and /ga/) results in shorter latencies than a combination involving a non-plosive. Also, it has been observed that N100 latencies elicited by plosive-vowel combinations are similar in latency to tonal stimuli, like pure tones (Lawson and Gaillard, 1981).

The P200 response is an exogenous, automatic response to auditory stimuli. The P200 can be elicited by speech stimuli (Tremblay and Kraus, 2002). Like the N100 response, the P200 response is affected by attention to the stimulus. The P200 amplitude increases with attention (Picton and Hillyard, 1974), however, the P200 can be recorded from a sleeping subject (Picton, 1974). The P200 amplitude is smaller in children than adults (Kraus, McGee, Carrell, Sharma, Micco, and Nicol, 1993). The P200 response is not affected by monaural versus binaural auditory stimulation (Picton, 1974). Training to auditory stimuli is reflected in the amplitude of the P200 response such that P200 amplitude increases with training (Tremblay and Kraus, 2002).

The N200 is associated with pattern recognition and stimulus classification. The N200 response can exhibit both exogenous characteristics, which depend on stimulus properties and endogenous characteristics, which dependent on stimulus characteristics and internal events, like cognition. Therefore, it can be elicited with a physical discrimination task, related to exogenous factors, or a semantic discrimination task, related to endogenous factors (for review see McPherson, 1996). Stimulus change or missing stimuli can elicit the N200 response. Perceptual processing and registration of a stimulus change reflected by the N200 response is preconscious and likely involves stimulus evaluation and classification processes. The N200 can be evoked from any sensory modality and across modalities. Thus, the N200 is thought to represent neural networks involved in intermodal processing. The N200 is usually recorded from Cz. It is believed that the generators of the N200 wave may lie within secondary visual and auditory cortical areas (for review see Stapells, 2002). Attention plays a role in the N200 response. If the listener is attending to the stimuli, the resulting N200 will be of greater magnitude than when the listener ignores the signal (McPherson, 1996). The N200 response is affected by hearing loss. Mild to moderate hearing loss has little effect on N200 amplitude, but results in prolonged N200 latency (Oates, Kurtzberg, and Stapells, 2002).

MMN is elicited using an oddball paradigm, in which a repeating stimulus (the standard stimulus) is pseudo-randomly replaced by a different stimulus (the oddball or deviant stimulus). MMN has been observed as a negative deflection that is passively elicited, automatic response to a stimulus change. Acoustic contrasts, such as a change in intensity, frequency or duration, elicit a MMN. A change in a complex sound, such as speech syllables or an auditory pattern, can also elicit MMN. MMN responses reflect the ability of the CANS to discriminate between sounds with small acoustical and phonetic differences. An oddball paradigm is used in eliciting responses to stimuli that are acoustically and phonetically different for MMN measures. Measurement of MMN may be of value in gaining more information of the central auditory system's processing of such cues as formant onset frequency in perception of the speech sounds /p/ and /t/. It is possible that MMN studies are highly correlated with perception and reflective of the CANS processing of these sounds (for review see Naatenan, 1995; Kraus, McGee, Carrell, and Sharma, 1995). The MMN is thought to be generated primarily in the superior plane of the temporal lobe, but also has contributing generators in the frontal lobe (Alho, 1995).

The P300 response is categorized as an event related potential (ERP) because its presence is dependent upon an event or change in stimuli. An ERP is an evoked potential measurement that is elicited by an endogenous response to an external event. P300s are elicited using an oddball paradigm, in which a repeating stimulus (the standard stimulus) is pseudo-randomly replaced by a different stimulus (the oddball or deviant stimulus).

The P300 is dependent on the listener’s attention to, and conscious discrimination of, stimulus differences (for review see Kraus, & McGee, 1994; Butcher, 1994; Dalebout & Stack, 1999). The generators are thought to include the frontal cortex, centroparietal cortex, and the hippocampus (McPherson, 1996).

The long latency evoked responses, including MMN and P300, have been used in the objective evaluation of discrimination in normal hearing and hearing impaired individuals (Bellis, Nicol, and Krauss, 2000; Plyler and Ananthanarayan, 2001; Tremblay, Piskosz, and Souza, 2003). Attempts have been made to correlate these objective responses with behavioral measures to the same stimuli with varying degrees of success (e.g., Sams, Paavilainen, Alho, and Naatanen, 1985; Martin, Sigal, Kurtzberg, and Stapells, 1997; Tremblay, Kraus, McGee, Ponton, and Otis, 2001). One limitation in conducting research using the P300 response and the MMN is the lengthy duration of each recording session. Lengthy recording sessions along with challenging behavioral tasks can result in fatigue of the participant and possibly subject attrition.

The ability to discriminate one sound from another can be measured using a number of methods. Research in psychoacoustics focusing on signal detection has used behavioral methods such as P(c), d’, and measures of psychometric functions such as categorical boundaries and slopes. While these measures are known to be reliable, the results from these measures include listener participation and therefore involve that listener’s listening strategy and any biases associated with that strategy. Measures in electrophysiology, such as the N100, P200, and N200 responses, allow for the removal of these biases by removing active participation from the protocol. However, these measures are not as reliable as the behavioral measures. Therefore, it would be advantageous to record discrimination abilities using both behavioral and electrophysiological methods.

Frequency Discrimination and Speech Perception

Difficulties with speech perception, especially place of articulation of consonants, have long been recorded in individuals with hearing impairment (e.g., Owens and Schubert, 1968; Owens, Benedict, and Schubert, 1972; Byers, 1973; Sher and Owens, 1974; Reed, 1975, Ochs, Humes, Ohde, and Grantham, 1989). It has been suggested that different listeners with normal hearing may prefer different acoustic cues for identifying stop consonants (Hazen and Rosen, 1991). Frequency discrimination may play a role in speech perception, such as in the determination of place of articulation of stop consonants. The formant transition cue is the change in the frequency of the stop consonant to the frequency of the vowel, more specifically, the second and third formant vocalic steady-states (for review see Kent, 1992). The ability to discriminate these changes in frequency is important in the ability to determine the perception of place of articulation between stop consonants (for review see Borden et al., 1994; Ochs et al., 1989).

The perception of a change in frequency or frequency discrimination has been studied extensively. Normal-hearing individuals can discriminate as small a difference in frequency as 1% between pure-tone stimuli. Frequency discrimination depends on the interaction of signal intensity and frequency. Changes in intensity affect higher frequencies less than lower frequencies. The change in frequency discrimination acts in a logarithmic manner as the standard frequency changes. Frequency discrimination is better at higher frequencies than lower frequencies (Weir, Jesteadt, & Green, 1977). The typical onset frequencies of formant transitions for the second formant range from 800 to 2400 Hz (for review see Kent and Read, 1992). Studies involving the perception of stop consonants have indicated that individuals with normal hearing depend largely on the formant transition as a cue in the perception of the place of articulation (Delattre, et al., 1955; Hedrick, et al., 1995). However, hearing-impaired listeners do not rely on the formant transition cue as much as normal-hearing listeners (Hedrick et al., 1995). This lack of reliance may be due to difficulties of hearing-impaired listeners to discriminate small changes in frequency. It has been shown that hearing-impaired listeners have an elevated difference limen for frequency (DLF) as compared to normal-hearing listeners (Freyman and Nelson, 1987; Turner and Nelson, 1982; Hall and Wood, 1984; Grant, 1987; Zurek and Formby, 1981).

Difficulties in the perception of stop consonants by hearing-impaired individuals have been documented. Ochs et al. (1989) found that hearing-impaired listeners demonstrated impaired performance in the identification of place of articulation of the sounds /bi/, /di/, and /gi/. Four hearing-impaired listeners and eight normal-hearing listeners were presented with consonant-vowel (CV) stimuli varying in first and second formant transition durations. The normal-hearing group listened to stimuli in the presence of background noise intended to simulate a hearing loss. A three alternative forced-choice (3AFC) method was performed to determine syllable discrimination. Results indicated that the performance of both hearing-impaired and normal-hearing listeners' performance improved with increase of formant duration, but as a group, normal-hearing listeners performed better than hearing-impaired listeners in the discrimination of /bi/ and /di/ for formant transition durations. It was concluded that hearing-impaired listeners had more difficulty in the perception of the syllable /bi/ than normal-hearing listeners.

Reed (1975) reported that reaction times (RT) to identification and discrimination of vowel-consonant syllables of hearing-impaired individuals were different than RTs of normal hearing listeners. Nine hearing-impaired listeners and two normal-hearing listeners were presented with vowel-consonant (VC) syllable pairs and instructed to indicate if the syllables heard were "same" or "different". Reaction times were recorded. Reaction times of hearing-impaired listeners' were slower than the reaction times of normal-hearing listeners. The author suggested that hearing-impaired listeners employ a different processing strategy than normal-hearing listeners.

Sher and Owens (1974) found that listeners with high frequency hearing loss had difficulty with consonant identification. Thirty-five hearing-impaired listeners and twenty-eight normal-hearing listeners were given a sheet of 100 multiple-choice items. The listener was presented with a VC or a CV at 40 dB SL. The listener was asked to check the item that was presented. The performance of the hearing-impaired listeners was poorer than that of the normal-hearing listeners. It was concluded that listeners with impaired hearing have difficulty in phoneme identification, primarily with stop consonants in the initial and final position.

Individuals with hearing impairments depend largely on an acoustic cue related to the burst component of stop consonants (Hedrick et al., 1995). Hedrick et al. used three burst intensity levels to create three synthetic continua that ranged perceptually from /pa/ to /ta/. A reference intensity level was established based on the amplitude of the fourth formant of the vowel (/a/) following the consonant. The synthetic burst of energy was presented at 10 dB greater than the amplitude of the fourth formant, 10 dB less than the amplitude of the fourth formant, and at the same amplitude as the fourth formant. In a two-alternative-forced-choice (2AFC) paradigm, listeners with normal hearing and listeners with sensorineural hearing loss identified each presentation of the stimuli as either a /p/ or a /t/. A significant effect was found for the burst cue, as well as for the burst cue by group interaction. Hedrick et al. concluded that those individuals with impaired hearing failed to use, or used the formant transition as a cue less, than individuals with normal hearing for perception of place of articulation of these stop consonants.

Although it appears that reliance on the use of the formant transition cue by hearing-impaired listeners diminishes with hearing loss, changes in the processing of these cues can occur. Changes in presentation level of stop consonants have been shown to alter the perception of stop consonants differently for individuals with normal hearing than for individuals with hearing impairments (Plyler and Hedrick, 2002). In this study, 16 normal-hearing and 16 hearing-impaired subjects listened to stimuli drawn from a continuum ranging from /ba/ to /da/ to /ga/. Each subject performed a three interval forced choice identification task under headphones. The stimuli varied in formant transition onset frequency for the second formant and in presentation level of the syllable. The formant transition onset frequency ranged from 900 to 2300 Hz in 100 Hz steps.

Categorical boundaries were identified corresponding to the 50 percent point of each listener's psychometric function. Plyler and Hedrick found that changing the presentation level altered the perception of the stop consonants. The phonetic boundary shifted for both normal-hearing listeners and hearing-impaired listeners between presentation levels of 92 dB SPL and 62 dB SPL indicating that the frequency of the formant transition corresponding with the categorical boundary varied as the intensity of the presentation level varied. For both normal-hearing and hearing-impaired listeners, the /d/-to-/b/ boundary shifted upward in frequency with the decrease of presentation level. As the perception progressed from /d/ to /g/, the direction of boundary shift in frequency as presentation level differed for normal-hearing and hearing-impaired listeners. The hearing-impaired listeners' boundary shifted downward in frequency as presentation level decreased, while an upward frequency shift was observed for normal-hearing listeners. Boundary shifts for normal hearing listeners were significantly greater than that of listeners with hearing loss, suggesting that increases in signal presentation level were more effective in altering categorization for individuals with normal hearing than with hearing impairments. The authors concluded that although all subjects appeared to benefit from higher presentation levels, individuals with hearing impairments have greater difficulty than normal-hearing individuals in categorizing stop consonants, regardless of presentation level. An additional conclusion stated that the performance difficulties of hearing-impaired listeners may be due to a degraded ability to process dynamic spectral information found in the formant transition.

Byers (1973) investigated the initial consonant intelligibility of 12 hearing-impaired children, ages 10 to 16 years. Six hearing-impaired listeners with sloping, high-frequency losses and six with flat or trough shaped losses, were presented with monosyllabic words in the Fairbanks Rhyme Test at different intensity levels. The Fairbanks Rhyme Test uses open-ended responses and is designed to measure intelligibility of consonants in the initial position in a word. Stimuli were presented at 10, 15, 20, 30, and 40 dB above the child's speech reception threshold. The listener wrote the consonant sound to complete the stem of a word that was already printed on the answer sheet. Results indicated that increased presentation level improved intelligibility for stop consonants. The author concluded that intelligibility of initial stop consonants would increase with the use of amplification.

Sams, Paavilainen, Alho, and Naatanen (1985) studied frequency discrimination using both electrophysiological and behavioral methods. Six listeners were presented with 50 ms stimulus tones in an oddball paradigm. The standard tones were set at 1000 Hz with deviant tones of 1002, 1004, 1008, 1016, or 1032 Hz. All tones were presented in the right ear at 80 dB SPL. The probability of presentation of the deviant tone was 20%. Evoked potentials were measured in two conditions. In the first condition, the participants were asked to ignore the auditory stimuli while reading. The second condition involved the attention and active participation of the listener. The listeners were asked to press a button each time they were certain that the deviant stimulus was presented.

Results from the behavioral discrimination task using the oddball paradigm indicated a frequency discrimination threshold at approximately 1008 Hz (DLF = 8 Hz), with a d' = 1.71. The threshold was defined as 50% correct detection of the deviant stimuli. With the standard stimulus at 1000 Hz and the deviant stimulus of 1008 Hz, the percent of deviant stimuli detected was 43.8%. At the next larger frequency difference (standard = 1000 Hz; deviant = 1016 Hz), percent correct and d' also increased to 85.6% and 3.41, respectively.

In the ignore condition, the standard stimuli elicited N100 and P200 evoked-potential responses. The evoked potentials for deviant stimuli equal to 1002, 1004, and 1008 Hz did not tend to differ from the standard 1000 Hz stimulus. An N200 response was recorded from all but one participant with the 1016 and 1032 Hz deviant stimuli while an N200 response was recorded by two of the participants with the 1008 Hz stimuli. Consistent with the behavioral thresholds, grand average data in the attend or discrimination condition indicated that the 1008, 1016 and 1032 Hz deviant stimuli elicited an N200 response. The latency difference between the attend and discrimination condition was significant at Fz and Cz. The authors suggested that the N200 evoked response reflected the processing of a change in frequency at, or slightly above, the level of behavioral discrimination threshold.

Martin, Sigal, Kurtzberg, and Stapells (1997), investigated the effects of decreased audibility on electrophysiological and behavioral measures of ten normal hearing listeners to the speech sounds /ba/ and /da/. Simulating hearing loss, the effect of decreased audibility was produced by high-pass noise masking at 4000, 2000, 1000, 500, and 250 Hz at 65 and 80 dB SPL. The ability to discriminate, as reflected by d’, did not statistically change until the noise cutoff frequency was reduced to 1000 Hz or lower. As the noise cutoff of the high-pass masker decreased in frequency, the ability to discriminate decreased at a rapid rate suggesting the ability to differentiate between /da/ and /ba/ behaviorally decreases when the spectral information is masked or lacking.

The auditory evoked potentials examined included the N100, N200, and P300 responses. The behavioral measure of d’ was used to indicate discrimination. The stimuli were presented in an oddball paradigm. Electrophysiologically, when the stimuli were presented at 65 dB SPL, the N100 response was present for 1000 Hz or higher high-pass masking conditions but not for 500 or 250 Hz high-pass masking conditions. For the stimuli presented at 80 dB SPL, the N100 response was present in all testing conditions. As the high-pass noise cutoff decreased, the N100 amplitude decreased and the N100 latency increased. No differences in the N200 response were observed for the two different stimuli or the two presentation levels. The N200 response was identified for the

4000 and the 2000 Hz high-pass conditions only. The N200 amplitude decreased and latencies increased as the high-pass noise cut-off decreased. The N200 was present in the difference wave for the quiet condition. In the attend condition, the P300 response was present in the grand mean waveforms for both presentation levels. The P300 amplitude was significantly larger for the 80 dB SPL condition than for the 65 dB SPL condition to the deviant. It was concluded that, consistent with behavioral results, the ability to process the difference between /da/ and /ba/, as reflected by the N100 response and the N200 response, decreases when the spectral information is masked or lacking. Additionally, the maskers affected N100, N200, and P300 differently suggesting that not only are these responses affected by hearing loss but then may be affected differently by different configurations of hearing loss.

The ability to discriminate between two sounds, simple or complex, is impaired for listeners with hearing loss. This impairment transfers to an impairment in the perception of and discrimination between speech sounds, such as stop consonants. These difficulties by hearing-impaired listeners have been demonstrated using both behavioral and electrophysiological methods. Increasing the presentation level of the stimuli results in some improvement in this auditory processing, but is limited in application outside of the laboratory setting.

Bellis, Nicol, and Kraus (2000) studied the effects of aging on the perception of the formant transition as reflected by the P100 – N100 complex. Three groups of subjects with normal hearing were used in this study. The groups included fifteen children, eleven young adults and ten older adults. Stimuli consisted of synthesized CV syllables varying in the onset frequency of the third formant creating a /da/-to-/ga/ continuum. Just noticeable differences (JNDs) were obtained from all subjects using a four-interval, forced choice task in which two pairs of syllables were presented with one pair consisting of different stimuli. The subjects indicated which pair had the difference. Electrophysiological recordings were made from Tr and Tl. P100 and N100 response latencies were identified and the P100-N100 peak-to-peak amplitudes were calculated. The P100-N100 peak-to-peak amplitude was significantly larger for children than young or older adults. Results indicated that children and young adults demonstrated a greater temporal lobe asymmetry than older adults. It was concluded that neural representation of speech sounds is age related. It is speculated that this age-related effect contributes to poor speech perception in the elderly.

Tremblay, Piskosz, and Souza (2003) investigated the effects of age and age-related hearing loss on the perception of voice onset time (VOT) using the N100-P200 complex. Participants for this study included ten young adults with normal hearing, ten older adults with normal hearing, and ten older adults with hearing loss. Stimuli implemented in this study included synthesized CV syllables varying in voice onset time creating a /ba/-to-/pa/ continuum. A same-different behavioral task was used in conjunction with electrophysiological measures of the N100-P200 complex. Results indicated that younger and older adults with normal hearing performed better than older adults with hearing loss. The latency of the P100 response was not affected by age or hearing sensitivity, while the N100 and P200 latencies were prolonged for older listeners. The amplitude of the P100 response was not affected by age or hearing sensitivity, while the N100 was larger for older listeners with hearing loss. It was concluded that aging and age-related hearing loss are factors in the difficulty of discriminating speech sounds due to an altered temporal processing of older adults with hearing loss.

Training and Generalization

Frequency Discrimination. The difference between formant onset frequencies of the /b/ and /d/ sound is a change in frequency within the speech signal. It is thought that detection and processing of this cue is based primarily upon the listener's frequency discrimination ability. It has been shown that individuals with normal hearing can improve their frequency discrimination ability with training (Demany and Semal, 2002; Irvine, Martin, Klimkeit, and Smith, 2000), while there is no information about changes in frequency discrimination of hearing-impaired listeners following training. Thus, the CANS is plastic and can be modified with experience. The effects of training on behavioral and electrophysiological responses may provide insights into the characteristics of learning as well as the mechanisms underlying the changes associated with training and learning (Wright, 2001).

Using a frequency discrimination task, Irvine et al. (2000) investigated human auditory perceptual learning of frequency specificity among 16 normal-hearing listeners. The digitally generated tone-burst stimuli were presented to the right ear at 60 dB SL via a supra aural headphone. The study consisted of four phases, including a preliminary task-practice, a pretest, a training, and a post-test phase. DLFs were obtained at 5 and 8 kHz from all participants during the pretest. Eight participants received frequency discrimination training at 5 kHz while the other eight participants received the same training at 8 kHz.

DLFs were obtained from each subject in all phases of the study using an adaptive, three-interval, 3AFC paradigm. Three DLF estimates were taken for both 5 and 8 kHz in the pre- and post-test phases. Eight DLFs were measured for each training session. The training phase consisted of nine sessions, with no more than two sessions per day. Irvine et al. found a reduction in DLF with training. DLFs decreased from pre- to post-test for both 5 and 8 kHz. A significant difference was found between DLFs of the individuals trained on one frequency and the DLFs from individuals not trained on that frequency. However, DLFs decreased for both frequencies. This difference occurred at both 5 kHz and 8 kHz, indicating a transfer of learning.

In an effort to study the frequency specificity of frequency discrimination learning, Demany and Semal (2002) trained eight subjects to discriminate a 3000 Hz tone presented monaurally from tones of slightly different frequencies presented in the same ear. Transfer of perceptual learning of frequency discrimination was assessed by measuring ipsilateral frequency discrimination thresholds for pure tones near 1200 Hz and 6500 Hz, and by measuring contralateral frequency discrimination thresholds near 3000 Hz. Using a three-interval, two alternative forced-choice (3I2AFC) procedure, stimuli were presented in noise. Participants were given visual feedback immediately after each correct response in an adaptive procedure. Each subject's discrimination threshold was based on the median of the shifts collected from the final 100 trials. Significant training effects were indicated from the first session to the last session. Significant changes between pre and post-training of the untrained frequency indicated some transfer of learning across frequencies. However, results related to the transfer of learning from the ipsilateral "trained" ear to the contralateral ear were inconclusive, as they conflicted with one another, questioning the validity of the measurement in comparing the two conditions.

Speech Perception. Walden, Erdman, Montgomery, Schwartz, and Prosek (1981) studied the effect of training consonant recognition on thirty-five hearing-impaired subjects, while using hearing aids. All subjects participating in the study had high-frequency, sensorineural hearing losses. Two groups of ten subjects participated in auditory or visual training. After training, both groups of ten and an additional fifteen subjects participated in a two-week aural rehabilitation program which included hearing aid orientation, speech-reading training, auditory training, hearing conservation, assertiveness training, speech conservation, and adjustment counseling. Auditory training consisted of fourteen thirty-minute sessions equaling seven hours of consonant recognition training spread over ten days. Before any auditory training was initiated, each subject had his/her hearing aids adjusted to a comfortable listening level, and a pre-test consonant identification score was obtained. The pre-test consisted of listening to the vowel-consonant-vowel (VCV) stimuli and writing down what was heard in an open set response. A same-different paradigm between VCV syllable pairs was used during the training. Feedback was given for each correct response. For incorrect responses, the previous presentation was repeated until the correct response was selected. The position of the consonant in the syllable varied. In addition to the same-different task, the subjects were presented with a syllable and ask to identify the syllable in an open set format. The results indicate an improved performance in the consonant identification test from a pre-training value of 68.9% to a post-training value of 80.5%. Walden et al. concluded that individuals with hearing loss improved their ability to identify consonants following auditory training on that consonant.

The ability to categorize stop consonants has been shown to be modified with auditory training (Pisoni, Aslin, Perey, and Hennessy, 1982). Identification ability was measured in 12 normal hearing subjects using an ABX discrimination test using 15 synthetic speech stimuli drawn from a continuum of stops consonants. The continuum varied in VOT, ranging from voiced (e.g. 20 ms) to voiceless (e.g. 40 to 80 ms) unaspirated to voiceless aspirated. Using the ABX paradigm, discrimination training involved four, one-hour sessions, conducted on consecutive days. Training stimuli included VOTs of –70, 0, and 70 ms. Feedback was given for each correct response. Based on the slope of the psychometric functions obtained, Pisoni et al. reported that naive listeners can perceive additional perceptual contrasts after auditory discrimination training.

Tremblay, Kraus, McGee, Ponton, and Otis (2001) used the voice-onset-time (VOT) speech cue in an effort to determine if training-induced changes are reflected in the N100-P200 complex. Using 10 normal-hearing subjects, pre- and post-training behavioral identification ability was measured using a two alternative forced-choice paradigm using synthetic speech stimuli drawn from a continuum of labial stops consonants. The continuum varied in voice onset time (VOT) from /ba/ to /pa/. For comparison, N100 and P200 auditory evoked potentials were recorded for stimuli with VOT of –20 ms and –10 ms during the pre- and post-training sessions.

After two days of pre-training evaluations, seven days of auditory training on VOT was performed, followed by a final post-training evaluation. Results indicated that performance improved with training. The average percent correct identification improved from 56% correct before training to 82% correct after training. Concurrently, the N100-P200 peak-to-peak amplitude significantly increased. It was concluded that training improved performance of identification of the VOT cue. It was also concluded that the N100-P200 complex reflects changes in neural activity brought about by auditory training.

In a subsequent study, Tremblay and Kraus (2002) investigated the amplitudes of P100, N100, and P200 before and after training seven normal-hearing listeners to the discriminate novel VOTs. Hemispheric symmetry of responses was also examined. The same stimuli, training procedures, and recording methods used in Tremblay et al. (2001) were incorporated into this study. Behaviorally, the ability to discriminate between the two VOTs significantly improved from 56% to 81%. The amplitudes of both the N100 and P200 response increased with the improved perception of the VOT cue at electrode sites Fz, Cz, and Pz. The amplitude of the P100 response decreased from pre to post-training at the Cz electrode site. When comparing pre and post-training responses from the right and left hemisphere, electrode sites Fl and Fr, the P100 and N100 amplitudes changed significantly at Fr. The P100 amplitude decreased while the N100 amplitude increased after training. The P200 amplitude significantly increased over both hemispheres following training. It was concluded that the electrophysiological responses, P100, N100, and P200, reflect changes in auditory processing following training and reflect hemispheric specializations.

As stated previously, the effects of training provide information about the characteristics of learning and the mechanisms underlying learning. This also holds true for generalization (Wright, 2001). According to Lerner et al. (1986), generalization is a transfer of learning resulting in a response to a stimulus different than, but similar to, the stimulus associated with training. Tremblay, Kraus, Carrell, and McGee (1997) found generalization effects after training nine normal hearing listeners to identify a prevoiced labial stop sound. A Same-Different paradigm using stimulus pairs drawn from a continuum of labial stop consonants was measured from nine untrained listeners (control group) and nine trained listeners (experimental group). The continuum varied in voice onset time (VOT) from /ba/ to /pa/. In addition to the Same-Different task for labial stimuli, listeners performed the same task for aveolar stop consonants. The aveolar stimuli continuum varied in VOT from /da/ to /ta/. Baseline MMNs were recorded for both labial and aveolar stimuli.

After baseline behavioral and electrophysiological data had been collected from the 18 participants, half of the group participated in nine training sessions over five days. Training of discrimination of VOTs for the different labial stimuli included visual feedback. Behavioral and electrophysiological data were collected after training from all 18 participants in the same manner as the baseline data.

The listening training improved behavioral discrimination performance for both the labial and the aveolar stimuli. The behavioral results were reflected by the MMN duration and area. It was concluded that training alters the perception of novel information, specifically, the discrimination between two very similar sounds. In addition, it was concluded that the training generalized to a speech sound with a different place of articulation, the aveolar stop. Changes in the MMN indicate neurophysiological changes associated with the training and the transfer of training.

<u>Cue Enhancement</u> Listeners use different acoustic cues within the speech signal to discriminate one speech sound from another (for review see Borden et al., 1994). Individuals with hearing loss have difficulty using many of these cues. It has been shown that some of these speech cues can be enhanced by amplification, or lengthening their duration (Revoile et al., 1987; Revoile et al., 1986; Holden-Pitt et al., 1986). Speaking clearly can enhance some of these speech cues as well (Picheny, Durlach, and Braida, 1985; Picheny, Durlach, and Braida, 1986).

Picheny et al. (1985) found that intelligibility of speech improves for individuals with hearing impairment when certain aspects of speech are enhanced. One aspect of speech that improves in clear speech is the production of stop consonants. Picheny et al. reported that speaking clearly versus conversational speech resulted in enhanced presentation of stop consonants. Stop consonants using clear speech were 10 dB more intense than stop consonants using conversational speech.

Picheny et al. discovered that hearing impaired listeners' speech intelligibility improved when the speaker speaks clearly compared to speaking conversationally. For clear speech, the speakers in the study were instructed to enunciate consonants carefully and speak as if trying to communicate with a hearing-impaired listener in a noisy environment. Speaking clearly incorporated using a constant rate, yet not speaking mechanically. For conversational speech, speakers were told to recite passages in a manner characteristic of a typical conversation. Subjects were presented with sentences and asked to repeat the sentences in writing or orally. Subjectively, the five subjects with moderately-severe to profound hearing loss reported that clear speech was more intelligible than conversational speech. Increased intelligibility scores also indicated that clear speech was more intelligible than conversational speech.

In a second experiment by Picheny et al. (1986), the speech samples of the three speakers used as conversational and clear speech in the initial experiment were analyzed. Clear speech differed from conversational speech in decreased speaking rate, prolonged pauses between words, and lengthened individual speech sounds. It was also observed that, in clear speech, stop consonants in the final position were released versus often not being released in conversational speech. Clear speech resulted in higher intensity presentation of stop consonants than conversational speech by as much as 10 dB.

Consistent with this finding, Revoile et al. (1987) showed that auditory training using enhanced speech cues improved the perception of stop consonants for hearing-impaired listeners. Twenty listeners with severe/profound hearing impairments were presented with utterances ending in stop consonants. The stimuli were digitized and the stop consonants were amplified. Final stop voicing perception was measured using a word identification task. The perception of stop consonants was better for words with enhanced cues than for the unmodified words.

The listeners then participated in training that involved speech stimuli with and without enhancement. Perception of the stop consonants improved by 29% for the enhanced stimuli following training and 10% for the unmodified words. It was concluded that cue enhancement resulted in improved consonant voicing perception.

Revoile et al. (1986) investigated the effect of cue enhancement on twenty-one hearing-impaired listeners. The stimuli consisted of unmodified digitized CVC speech utterances. Enhancement of the stimuli included using low-pass filters, lengthening the duration, and increasing the intensity of voiceless fricatives in the final position. A four alternative forced-choice task was used for testing syllable identification performance. Syllable identification performance improved from 62% with unmodified stimuli to 85%

with enhanced stimuli. It was concluded that consonant perception improves with enhancement of certain acoustic segments.

Revoile et al. (1986) studied the perception of unmodified and enhanced fricatives in the final position in individuals with hearing impairment. The effects of auditory training on these perceptions were also investigated. Twenty-five listeners with moderate to severe hearing impairments served as subjects. The subjects were divided into three groups according to their performance on the initial unmodified syllable identification test and performance following training on unmodified syllables. The groups included a good, intermediate, and poor group. In order to be placed in the good group, a score of 70% or higher was required on the initial unmodified syllable identification test. The intermediate group consisted of listeners scoring below 70% on the initial test, but above 70% following training on unmodified syllables. Listeners scoring below 70% both before and after training were assigned to the poor group.

Digitized utterances were used for stimuli. The utterances were ranked and placed into subsets of easy, moderate and difficult, according to vowel duration. After initial syllable identification testing using the unmodified stimuli, listeners participated in training. The oddity and paired-comparison paradigms were used to train the listeners over a couple of sessions. Deleting or iterating pitch periods enhanced the stimuli. Deleting every other pitch period in the mid-vowel region of the utterance decreased the role of the vowels preceding voiceless fricatives. Adjacent pitch periods were repeated to increase the durations of vowels preceding voiced fricatives. Results indicated that the subjects' performance in perceiving fricative voicing for enhanced stimuli was better than for unmodified stimuli for all of the groups in this study.

The final stage of the study involved the post-training performance on the unmodified syllable identification test. Significant improvement was recorded from the good group and the intermediate group. Changes in the poor group were not statistically significant; they performed near 50% correct for both the initial and final tests indicating little use of the enhanced cue before or after training. Those individuals with hearing impairment who appeared to rely on the enhanced cue (the intermediate group) improved in final fricative voicing perception. Subjects in the poor group, performing at chance level, never showed use of the enhanced cue before or after training. Subjects in the good group showed only a small amount of improvement, indicating a ceiling effect, because their perception of the unmodified fricatives was good without enhancement. Revoile et al. stated that conclusions regarding the effects of training were limited by the restricted nature of the training procedures.

Listeners with both normal hearing and hearing loss have the ability to be trained to improve auditory processing. Improvements in auditory processing range from an increased ability to discriminate between pure tones of different frequencies to better speech-sound discrimination ability. Cue enhancement improves these abilities, but is limited in application outside of the test setting. However, cue enhancement may be useful in the auditory training protocol used to help hearing-impaired listeners improve discrimination abilities outside the laboratory.

Justification

Behavioral and electrophysiological measures reflect stimulus discrimination abilities of normal-hearing and hearing-impaired subjects. Detection and use of formant transitions for behavioral CV discrimination is impaired in those subjects with hearing loss. While it has been shown that hearing loss is reflected in late auditory evoked potentials, it is not clear if the use or difficulty in the use of the formant transition cue is reflected in these electrophysiological measures. If electrophysiological measures accurately represent this impaired processing, the information would be useful in rehabilitating these patients.

It is not known if the use of the formant transition cue will be strengthened in these individuals following enhancement of the cue and training on the enhanced cue. Nor is it known if training of a speech sound in the initial position of a CV syllable will transfer to an improved processing of a speech sound in the final position of a VC syllable. If the use of the formant transition cue is strengthened following training on the enhanced cue and the training generalizes to other sounds, it may have clinical implications in the development of auditory training in aural rehabilitation.

It would be of interest to see if changes in perception are reflected by both behavioral and electrophysiological measures and then, to compare the results of auditory training. If detection and use of formant transitions are reflected in auditory evoked potentials, then evoked potentials could be a valuable tool in the assessment of efficacy of auditory training, along with behavioral measures.

Research Questions

1) Can hearing-impaired listeners be trained to increase or improve use of the formant transition cue? Improved frequency discrimination can be trained in normal-hearing listeners (Irvine et al., 2000; Demany and Semal, 2002). Training has been shown to improve categorization abilities of stop consonants by normal-hearing listeners (Pisoni et al., 1982; Tremblay et al., 2001; Tremblay et al., 1997). Training has been shown to improve the ability to identify stop consonants for hearing-impaired listeners (Walden et al., 1997). However, the stimuli were recordings of clear speech, not synthetically-enhanced speech. More information about training hearing-impaired listeners may be obtained by deriving a psychometric function of the listener's perception and by recording auditory evoked potentials elicited by unmodified and enhanced consonants.

2) Can training hearing-impaired listeners with enhanced cues generalize to improved perception of unmodified stop consonants or stop consonants in the final position? Irvine et al. (2000) and Demany and Semal (2002) demonstrated that training of better frequency discrimination could generalize to another frequency. These studies reported the training and generalization improved frequency discrimination of pure tones, not speech cues. Tremblay, Kraus, Carrell, and McGee (1997) found training nine normal hearing listeners to identify a pre-voiced labial stop sound generalized to improved discrimination of a pre-voiced aveolar stop. This study examined the training and generalization of VOT, a temporal speech cue. Little is known about hearing-impaired

listeners ability to be trained to improve the ability to discriminate or if the training will generalize to other stimuli, as indicated by either behavioral or electrophysiological measures.

3) Do behavioral and objective measures of perception of stop consonants correlate in hearing-impaired listeners? Sams et al. (1985) found, in the measurement of frequency discrimination in normal-hearing listeners, that the sensitivity of electrophysiological measures reflected the sensitivity of behavioral measures. It is unknown if electrophysiological and behavioral measures of discrimination of the formant transition cue will correlate well in hearing-impaired listeners.

Purpose

The aims of this study were threefold: (1) to determine if hearing-impaired listeners could increase or improve their perception of stop consonants with training, (2) to determine if hearing-impaired listeners trained with enhanced cues could generalize to improved perception of unmodified stop consonants and/or stop consonants in the final position, (3) to document the correlation, if any, between behavioral and electrophysiological responses before, during, and after training.

CHAPTER III
Methods

Participants

Eleven individuals (seven male, four female) with sensorineural hearing loss participated in this study. The subjects ranged in age from 23-72 (mean = 57, median = 63) years. All subjects were tested to ensure that hearing threshold levels were between 30 dB HL and 65 dB HL from 1000 to 4000 Hz (ANSI S3.6-1996). The pure tone average for the subjects in this study was 48.5 dB HL at 1000, 2000, and 4000 Hz. Subject age, hearing loss, sex, and hearing aid use are displayed in Table 1. Tympanometry was performed on all participants to ensure normal middle ear function. All subjects were native English speakers with no known neurological, cognitive, or learning deficits, as reported by subjects.

Subjects in this study were interviewed and screened before participating in pre-training behavioral and electrophysiological recordings. Subjects returned to participate in auditory training on the enhanced formant transition cue in the second through fifth sessions and post-training measures in the sixth session. Post-training behavioral and electrophysiological recording procedures were identical to pre-training measures.

Stimuli

Synthetically-generated CV stimuli using the cascade configuration of a PC version of the Klatt synthesizer at a sampling rate of 10 kHz were used as stimuli for this study. The total duration of these CV stimuli was 100 ms. During the first 40 ms, the frequency of the second formant (F2) was in transition, and the last 60 ms of the syllable represented the vocalic steady-state, the vowel /a/. For stimuli altering the formant transition cue, the onset frequency of F2 varied from 900 Hz to 1700 Hz, with a steady-state of 1250 Hz (Figure 1). These values were associated with perception of the most /b/-like (F2=900 Hz) and /d/-like (F2=1700 Hz) sounds. F1 for all stimuli had an onset frequency of 400 Hz, and increased to a steady-state value of 750 Hz in 40 ms. Vocalic steady-state values were as follows: F1=750 Hz, F2= 1250 Hz, F3= 2400 Hz, F4= 3300 Hz. The formant transition component of the CV stimuli was enhanced by increasing the intensity level of the first 40 ms. by 16 dB. The CV stimuli was output from a D/A converter, low-pass filtered at 4.9 kHz, sent to an attenuator, sent to a headphone buffer, and routed to headphones located inside a double-walled sound booth.

Generalization stimuli differed from the experimental stimuli in that the formant transition followed the steady-state formants. In other words, the consonant followed the vowel (VC). The consonant was then in the final position, not the initial position. The duration of the steady-state portion of the stimuli was 40 ms while the consonant portion was 60 ms long. The level of the stimuli in all measurements in this study was at a maximum rms of 90 dB SPL. Laboratory testing equipment, both behavioral and electrophysiological, was verified for proper calibration before, during, and after data collection.

Interview/Screening

All participants were interviewed and screened during the first 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, 3) a case history was taken, asking specific questions about past and present ear infections, noise exposure, head trauma, and cognitive or learning deficits, and 4) if the subject had not had a hearing evaluation within the past year, the participant received a hearing evaluation, which included audiometric testing, tympanometry, and otoscopy. At the completion of the interview/screening session, behavioral and electrophysiological measurements were made and the subject was scheduled for training and the post-training experimental session.

Identification Testing (Days 1 and 6)

Subjects were seated in a sound treated test booth and instructed to view a computer monitor. Stimuli were presented monaurally, while the subjects were instructed to indicate which stop consonant they heard by selecting the appropriate symbol on the monitor (e.g. B or D). The subjects were asked to respond after each stimulus presentation. Each subject participated in a pre-experimental test session prior to experimental testing to familiarize the listener to the identification task.

Subjects were presented with each of the unmodified stimuli within the continuum in a random order using a 2AFC task to determine that subject's phonetic boundary. This boundary was identified corresponding to the 50% point of each listener's psychometric function. In order for a psychometric function to meet the criteria as a categorical boundary, there could not be more than one shift across the 50% point. Psychometric functions that did not meet the criteria were labeled as no boundary. In the case when no phonetic boundary was present, the stimulus farthest from the most /b/-like stimulus, corresponding to at least 70 % /b/ was identified. And the stimulus, farthest from the most /d/-like stimulus, corresponding to at most 30% /b/ was identified. This pair of stimuli was referred to as the subject's approximated boundary. If no responses reached 70% or 30%, the boundary was set between 1200 and 1300 Hz, approximately halfway between the two endpoints. This boundary was also referred to as an approximated boundary. The procedure was repeated using the generalization stimuli.

Random presentation of the stimuli and data collection was performed via a commercially available computer program (CSRE, Version 4.5). Each stimulus followed the subject's response to the previous stimulus by 250 ms. Each identification testing session lasted thirty to forty-five minutes.

Auditory Evoked Potentials (Days 1 and 6)

Auditory cortical evoked potentials N100, P200, and N200 were measured using a 4-channel electrode configuration using a commercially available evoked potential computer program (Biosig ©, version 32). Two hundred and fifty presentations of the stimuli immediately preceding and following the subject's categorical boundary or approximated boundary and the stimuli for both continuum endpoints were presented to the subject in a homogeneous sequence. A total of 1000 presentations of the experimental stimuli were presented to the listener. The stimulus parameters were consistent with those of the behavioral testing. The stimulus duration of 100 ms included 40 ms of transition and 60 ms of steady-state. The same procedure was followed for presentation of the generalized stimuli.

In order to keep electrode sites consistent across sessions, distances were measured between certain landmarks (e.g. nasium to Fpz) and recorded. The interstimulus interval (from onset of one stimulus to the onset of the next stimulus) of 900 ms was used.

Prior to placement of gold-plated electrodes, the skin was cleansed with a mild facial scrub and a conductive paste applied. The electrodes were held in place with medical tape. Electrode impedances were below 5 kHz and within 2 kHz of each other and measured at 30 Hz. The non-inverting electrodes were placed on the center vertex of the head (Cz), and at the temporal lobes (Tl and Tr). The Tl electrode was placed halfway between T3 and T5, while the Tr electrode was placed halfway between T4 and T6. The inverting electrodes were linked to one another and placed on the earlobes (A1&A2). The ground electrode was placed on the low forehead (Fpz) (Jasper, 1958). The electro-oculogram (EOG) was used to develop an eye-blink rejection rule for each subject. Electrode locations are displayed in Figure 2. 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 and muscle contractions. Before data collection began, deflections caused by eye blinks were recorded and the artifact rejection was set to match. Eye blinks were also monitored via video surveillance.

All responses 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, while the bandwidth was set at DC -30 Hz. An artifact rejection algorithm applied to the online averaging waveform. If the peak voltage within a sweep exceeds ±80 :V, that sweep was excluded from the averaged waveform. Each response was digitized over a 750-ms sweep duration via a 16-bit analog-to-digital converter (Tucker-Davis Technologies, model AD2). A total of 7500 points were averaged in a 750 ms time window, resulting in a sampling rate of 10 points per ms or a sample period of 100 microseconds.

While recording the responses, 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 to the test ear through an electrically-shielded insert earphone (Etymotic Research, model ER-3A). The level of the stimuli was 90 dB peak SPL. During the recording session, participants were instructed to sit quietly and ignore the syllables while watching a videotape in quiet or reading. Subjects were also instructed to stay awake during testing. The participants were given the opportunity to take breaks frequently during the testing. Each auditory evoked potential session required approximately one hour to record.

Identification Training (Days 2,3,4, and 5)

Subjects participated in auditory training for four days following the initial identification testing. Each participant was instructed to listen to single stimulus, random presentations of the enhanced CV stimuli with the formant transition onset frequency varying from 900 Hz to 1700 Hz in 100 Hz increments. The subjects were asked to identify each sound as either /ba/ or /da/ in a 2AFC paradigm. The response choices appeared on a computer screen as text. A green reinforcement flash, indicating correct identification, appeared on the screen each time the subject selected /da/ for the stimulus that had a higher formant onset frequency than the subject's categorical boundary or estimated boundary for subjects with no boundary. A green reinforcement flash, indicating correct identification, also appeared on the screen each time the subject selected /ba/ for the stimulus that had a lower formant onset frequency than the subject's categorical boundary or estimated boundary. Each subject's categorical boundary was programmed into the computer to determine if responses during training were consistent with the categorical boundary or estimated boundary established in the identification testing on the first day of testing. In the case in which a function did not reach the 70% or 30% level, the boundary was set at 2500 Hz for training purposes. Random presentation of the stimuli and data collection were performed via a commercially available computer program (CSRE, Version 4.5). Feedback to the response was presented 250 ms following the subject's response. Each stimulus followed the feedback from the previous stimulus by 250 ms. Identification training required about 15 to 45 seconds per block. Identification training sessions included 12 blocks of 36 trials per block for a total of 432 trials in which the onset frequency of the formant transitions varied along the continuum described previously. Four blocks were presented before the subject was offered a short break, followed by four more blocks, another break and the final four blocks. Thus, each training session lasted 20 to 45 minutes, depending on the response speed of the subject and duration of breaks between blocks of testing.

Data Analysis

Behavioral Data. The percentage of /b/ responses for each stimulus was recorded using Tucker-Davis Technologies software (Psychosig ©). These responses established the psychometric functions of the perception of voiced stop consonants /b/ and /d/ as reflected by the categorical boundaries for each participant for both pre-training and post-training sessions. The percentage of the number of /b/ responses established the ordinate for the psychometric function. The continuum of formant onset frequency for the stimuli ranging from 900 Hz to 1700 Hz formed the abscissa for the psychometric function. The slope of each psychometric function was determined by measuring the difference in height, or percent /b/ between the data point immediately before the categorical boundary from the data point immediately after the categorical boundary. That difference was divided by the distance, or change in onset frequency for the stimuli between those two points. Specifically, the two data points used for calculating the slope included the data point closest to the boundary on the /b/ side with at least a 70% /b/ response rate and the point closest to boundary on the /d/ side with at most a 30% /b/ response rate (Figure 3).

The difference in height between two parts of the function was measured. The difference is calculated between the height of one side of the categorical boundary and the height of the other side of the boundary of the same function. For this study, the calculation involved subtracting the height of the data point immediately following the boundary from the height of the data point immediately preceding the boundary. This calculation differs from that for the slope in that the two data points on either side of the boundary are used in the calculation regardless of the percentage of /b/ responses (Figure 4). This calculation also was performed for the mean of the two points immediately preceding and following the boundary and for the mean of the three points immediately preceding and following the boundary (Figure 5).

One single descriptive procedure, such as the slope of the function, or the difference in height between two parts of the function did not always represent the trend of the function well, across all functions. For example, the difference in height between two functions using one data point may represent one function well yet not represent another function as well as the difference in height using two or three data points. For this reason, in addition to the procedures above, the method that represented each subject's functions best was selected. This was referred to as the best descriptor.

Electrophysiological Data. Electrophysiological responses were elicited using stimuli from the endpoints of the continuum and stimuli closest to the boundary on the /b/ side and the point closest to boundary on the /d/ side. Electrophysiological waveforms were collected from electrode sites Cz, Tr, and Tl for both experimental and generalization stimuli. Waveforms from each subject were averaged to calculate grand averages waveforms for the group for each electrode location. The P200 response from individual waveforms, in conjunction with the grand average waveform as a guide, was used to identify P100, N100, P200 and N200 in individual waveforms. Amplitudes and latencies of individual and group waveforms were recorded for the experimental stimuli and the generalization stimuli. In the recordings where no clear P100 or N200 responses were present, peak-to-peak amplitudes were recorded as zero and a procedure of imputation was implemented for latency. The resulting values were inserted to represent the missing P100, and N200 latencies. The method of imputation was designed to fill in missing data with data points that will minimally affect any statistical analysis. For example, data entered for a missing P100 latency recorded at Cz, elicited by the stimulus with the formant onset frequency immediately preceding the categorical boundary, resulted in a change in mean latency from 121.8 ms to 121.5 ms and a change in standard deviation from 15.9 to 15.1. The method of imputation filled empty data cells, avoiding individual subject elimination from the statistical analyses due to only one or two absent peaks.

CHAPTER IV
Results

Behavioral Data

Qualitative Analysis. Psychometric functions and categorical boundaries of the perception of stop consonants were obtained for both pre and post training sessions (Figures 6-16). Descriptive statistics related to the psychometric functions are listed in the Appendix. Seven of the eleven subjects demonstrated monotonic psychometric functions at the initial testing session (Subjects 1, 2, 3, 5, 9, 10, and 11). Five of the eleven subjects' psychometric functions appeared to improve (Subjects 2, 3, 5, 7, and 9) while four of the subjects' functions did not indicate any change (Subjects 6, 8, 10, and 11) and two of the subjects' functions declined (Subjects 1 and 4). Two of the subjects' psychometric functions had minimal room for behavioral improvement (Subjects 10 and 11). For this study, improvement in a function required the labeling of the stimuli following training to be consistent with the categorical boundary more frequently than labeling of stimuli before training.

For responses to the generalization stimuli, two of the eleven subjects demonstrated psychometric functions for both pre and post training (subjects 3 and 5). No apparent improvement was observed. One subject failed to demonstrate categorical perception before, but exhibited a psychometric function after training (subject 10). All other participants failed to demonstrate categorical perception pre or post training.

Quantitative Analysis. A two factor analysis of variance (ANOVA) using a general linear model was performed to determine main effect for training (repeated measures on 2 levels, pre and post) and stimulus type (repeated measures on 2 levels, experimental and generalization) for the difference in height between two parts of a psychometric function computed using one data point on either side of the boundary. Training refers to the difference associated with measures made before and following training. Stimulus type refers to the comparison between the experimental stimuli and the generalization stimuli. Using a Bonferroni correction to account for multiple ANOVAs (see following sections), an alpha level of 0.01 (0.05 / 5) was required for achieving significance. Pillai's trace did not indicate a significant main effect for training ($F(1,10)=5.415$, $p=0.042$), stimulus type ($F(1,10)=3.041$, $p=0.112$) or interaction between training and stimulus type ($F(1,10)=2.238$, $p=0.166$).

Groups by Psychometric Function. Despite not finding a significant main effect for training on the group data, it was obvious that some individuals did improve. Therefore, investigation into the differences observed between these individuals, who did not improve, included dividing the subjects into two groups. Of the two groups, the first group had a monotonic psychometric function before training which ranged in the percentage of /b/ responses from at least 70% to at most 30%. This group consisted of seven of the eleven subjects participating in the study. The second group consisted of the remaining four subjects, who exhibited no clear categorical boundary in the psychometric function before training as indicated by a lack of monotonicity or a lack of reaching either at least 70% and at most 30% of the percentage of /b/ responses.

Two two-factor ANOVAs using a general linear model were performed to determine main effect for training (repeated measures for 2 levels, pre and post) with group (2 levels, with boundary or without boundary) as a between-subjects factor. The first ANOVA, using the difference in height measure, indicated no significant main effect for training (F(1,9)=0.128, *p* =0.729). There was no significant interaction between training and group (F(9,1)=0.404, *p* =0.541), indicating no difference in the effect of training on the subjects with an initial boundary, versus subjects with no initial boundary. Significance was not indicated for the between subjects factor for group (F=7.278, *p* =0.024).

The second ANOVA, using the best descriptor, found no significant main effect for training (F(1,9)=0.388, *p* =0.549), or the interaction between training and group (F(9,1)=0.552, *p* =0.477). These results also indicate no difference in the effect of training on subjects with an initial boundary, as compared to subjects without an initial boundary. Significance was indicated for the between subjects factor for group (F=1.276, *p* =0.004), with subjects who had an initial boundary (mean=0.09526) having larger difference values from training than those subjects with no initial boundary (mean= -0.008325).

Groups by Age. The subject pool was divided into two groups according to age. The first group consisted of seven subjects over the age of 55 years. Of the seven participants over 55 years, three demonstrated monotonic functions at the initial session. The four subjects younger than 55 years were assigned to the second group. All four subjects below the age of 55 years demonstrated monotonic functions at the initial session.

Two ANOVAs for repeated measures using a general linear model were performed to determine main effect for training (repeated measures for 2 levels, pre and post) with age as a between-subjects factor (2 levels, above 55 years and below 55 years). The first ANOVA used the difference in height measure. Pillai's trace did not indicate a significant main effect for training (F(1,9)= 0.043, *p* =0.841), or for interaction between training and group (F(9,1)=1.749, *p* =0.219) indicating the lack of any significant training effect on the group of subjects over 55 years, versus the group of subjects under 55 years. Significance was not indicated for the between subjects factor for group (F=0.864, *p* =0.377).

Based on the best descriptor, the second ANOVA found no significant main effect for training (F(1,9)=1.106, *p* =0.320), the interaction between training and group (F(9,1)=0.658, *p* =0.438). The results indicate no difference in the effect of training on one age group of subjects compared to the other age group of subjects. No significant effect was indicated for the between subjects factor for group (F=3.204, *p* =0.107).

Electrophysiological Data

Electrophysiological responses to both experimental and generalization stimuli were collected at Cz, Tr, and Tl and averaged to calculate grand averages waveforms for each electrode location. Amplitudes and latencies of individual waveforms were recorded for the experimental stimuli and the generalization stimuli.

ANOVAs for repeated measures using a general linear model were performed to determine main effect for training (2 levels), stimulus type (2 levels), and electrode location (3 levels) for the P100, N100, P200, and N200 response latencies and for the P100-N100, N100-P200, P200-N200 peak-to-peak amplitudes evoked by each of the four stimuli used per subject. Using a Bonferroni method of correction to account for multiple ANOVAs, an alpha level of 0.002 (0.05 / 28) was required for achieving significance. Descriptive statistics including means and standard deviations for all dependent variables are presented in the Appendix.

Onset Frequency of 900 Hz. Pillai's trace indicated no significant main effect in the P100 response evoked by a formant transition onset of 900 Hz for training (F(1,10)= 2.179, *p* =0.171), stimulus type (F(1,10= 3.092, *p* =0.109), or electrode location (F(2,9)= 0.867, *p* =0.453). A significant interaction was found between training and electrode location (F(2,9)= 20.983, *p*<0.001) indicating that from pre to post training, the latency measured at Cz increased from 120 to 132 ms, as the latency decreased at Tr from 130 to 127 ms, and the latency increased at Tl from 124 to 126 ms (Figure 17). No other interactions were found to be significant.

For the P100-N100 peak-to-peak amplitude elicited by the stimulus with a formant transition onset of 900 Hz, Pillai's trace indicated no significant main effect for training (F(1,10)= 0.878, *p* =0.371), stimulus type (F(1,10) = 5.871, *p* =0.036), or electrode location (F(2,9)= 5.955, *p* =0.023). None of the possible interactions were found to be significant. For the N100 responses to the stimulus with a formant transition onset of 900 Hz, Pillai's trace indicated no significant main effect for training (F(1,10)= 0.75, *p* =0.790), stimulus type (F(1,10= .2904, *p* =0.119), electrode location (F(2,9)= 1.819, *p* =0.217), or possible interactions.

Pillai's trace indicated no significant main effect in the N100–P200 peak-to-peak amplitude for training (F(1,10)= 0.008, *p* =0.931), or stimulus type (F(1,10= 2.329, *p* =0.158), but there was a significant effect for electrode location (F(2,9)= 30.591, *p* <0.001). The mean N100-P200 peak-to-peak amplitudes recorded at Cz, Tr, and Tl were 3.189, 1.549, and 1.234 µV, respectively. None of the possible interactions were found to be significant. Post-hoc pairwise comparisons of N100-P200 peak-to-peak amplitudes for electrode locations were performed. Using the Sidak adjustment for multiple comparisons, significant differences were indicated between electrode placements at Cz and Tr (mean difference = 1.640µV, *p* < 0.001), and between electrode placements at Cz and Tl (mean difference = 1.955µV, *p* < 0.001), but not between electrode placements at Tr and Tl.

For the P200 responses to the stimulus with a formant transition onset of 900 Hz, Pillai's trace indicated no significant main effect for training (F(1,10)= 0.237, *p* =0.637), stimulus type (F(1,10= 1.872, *p* =0.201), electrode location (F(2,9)= 0.74, *p* =0.504), or possible interactions. No significant main effect was found in the P200–N200 peak-to-peak amplitude for training (F(1,10)= 0.990, *p* =0.343), stimulus type (F(1,10= 0.993, *p*

=0.343), electrode location (F(2,9)= 1.449, *p* =0.285) or possible interactions. For the N200 responses, Pillai's trace indicated no significant main effect for training (F(1,10)= 0.274, *p* =0.612), stimulus type (F(1,10= 0.525, *p* =0.485), or electrode location (F(2,9)= 3.937, *p* =0.059). No interactions were found to be significant.

<u>Onset Frequency Preceding the Boundary</u>. Pillai's trace indicated no significant main effect in the P100 response evoked by the formant transition onset equal to the stimulus immediately preceding or on the /b/ side of the categorical boundary for training (F(1,10)= 0.433, *p* =0.526), stimulus type (F(1,10= 0.170, *p* =0.688), or electrode location (F(2,9)= 2.627, *p* =0.126). No significant interactions were indicated. No significant main effect was found for the P100-N100 peak-to-peak amplitude for training (F(1,10)= 1.421, *p* =0.261), stimulus type (F(1,10) = 5.877, *p* =0.036), electrode location (F(2,9)=5.145, *p* =0.032), or any of the possible interactions. For the N100 absolute latencies, no significant main effect for training (F(1,10)= 1.759, *p* =0.214), stimulus type (F(1,10= .883, *p* =0.370), electrode location (F(2,9)= 1.365, *p* =0.304), or interactions was indicated.

No significant main effect was indicated for N100-P200 peak-to-peak amplitude for training (F(1,10)= 1.906, *p* =0.198), stimulus type (F(1,10) = 6.469, *p* =0.029), but a significant main effect was found for electrode location (F(2,9)= 40.782, *p* <0.001). The mean P100-N100 peak-to-peak amplitudes recorded at Cz were the most robust (2.773 µV) followed by those at Tr (1.509 µV), and then Tl (1.096 µV). No significant interactions were indicated. Post-hoc pairwise comparisons of N100-P200 peak-to-peak amplitudes for electrode locations were performed. Using the Sidak adjustment for multiple comparisons, significant differences were indicated between electrode placements at Cz and Tr (mean difference = 1.64, $p < 0.001$) and electrode placements at Cz and Tl (mean difference = 1.677, $p < 0.001$), but not between electrodes placed at Tr versus Tl.

For the P200 responses, Pillai's trace indicated no significant main effect for training (F(1,10)= 1.155, p =0.308), stimulus type (F(1,10= 0.178, p =0.682), electrode location (F(2,9)= 0.883, p =0.446), or any interactions. Pillai's trace indicated no significant main effect in the P200–N200 peak-to-peak amplitude for training (F(1,10)= 0.336, p =0.575), stimulus type (F(1,10= 0.12, p =0.916) or electrode location (F(2,9)= 4.541, p =0.043). Significant interactions were not indicated. No significant main effects were found in the mean N200 absolute latencies for training (F(1,10)= 0.336, p =0.575), stimulus type (F(1,10= 7.072, p =0.024), or electrode location (F(2,9)= 3.021, p =0.099). None of the possible interactions among N200 factors were found to be significant.

Onset Frequency Following the Boundary. Pillai's trace indicated no significant main effect in the P100 response to the stimulus with a formant transition onset equal to the stimulus immediately following or on the /d/ side of the categorical boundary for the main effects of training (F(1,10)= 0.117, p =0.739), stimulus type (F(1,10= 0.254, p =0.625), or electrode location (F(2,9)= 1.198, p =0.346). No significant interactions were indicated.

Pillai's trace indicated no significant main effects for the P100–N100 peak-to-peak amplitude for training (F(1,10)= 6.019, p =0.034), stimulus type (F(1,10= 4.420, p =0.062), or electrode location (F(2,9)= 3.847, p =0.062). All interactions lacked significance. For the N100 response, no significant main effect for training (F(1,10)= 0.880, p =0.370), stimulus type (F(1,10= 0.195, p =0.668), or electrode location (F(2,9)= 3.472, p =0.076) was found. No significant interactions were indicated.

No significant main effect for The N100-P200 peak-to-peak amplitude for time (F(1,10)= 10.287, p =0.009), or signal type (F(1,10) = 6.736, p =0.027), but a significant effect was found for electrode location (F(2,9)= 36.074, p <0.001). Mean amplitudes of the N100-P200 response were larger at Cz (3.070 μV), than Tr (1.551 μV), or Tl (1.123 μV). No significant interactions were indicated. Post-hoc pairwise comparisons of P100-N100 peak-to-peak amplitudes for electrode locations were performed. Using the Sidak adjustment for multiple comparisons, significant differences were indicated between electrode placements at Cz and Tr (mean difference = 1.519, $p < 0.001$) and electrode placements at Cz and Tl (mean difference = 1.947, $p < 0.001$), but not between electrode placements at Tr and Tl.

For the P200 response, Pillai's trace indicated no significant main effect for training (F(1,10)= 0.377, p =0.553), stimulus type (F(1,10= 2.746, p =0.129), or electrode location (F(2,9)= 1.776, p =0.224). No significant interactions were indicated. Pillai's trace indicated no significant main effect in the P200–N200 peak-to-peak amplitude for training (F(1,10)= 1.991, *p* =0.189), stimulus type (F(1,10= 2.092, *p* =0.179), or electrode location (F(2,9)= 3.727, *p* =0.066). None of the possible interactions were significant.

No significant main effect was found for the N200 response for training (F(1,10)= 0.014, *p* =0.907), stimulus type (F(1,10= 1.996, *p* =0.188), electrode location (F(2,9)= 0.332, *p* =0.726) or any of the possible interactions.

<u>Onset Frequency of 1700 Hz</u>. Pillai's trace indicated no significant main effect in the P100 response evoked by a stimulus with a formant transition onset of 1700 Hz for training (F(1,10)= 1.102, *p* =0.319), stimulus type (F(1,10= 3.235, *p* =0.100), electrode location (F(2,9)= 1.529 *p* =0.268). No significance was indicated for any of the possible interactions. For the P100-N100 peak to peak amplitude, Pillai's trace indicated no significant main effect for training (F(1,10)= 6.296, *p* =0.031), stimulus type (F(1,10) = 6.568, *p* =0.028), and electrode location (F(2,9)= 4.834, *p* =0.038), or any possible interactions.

No significant main effects for training (F(1,10)= 0.627, *p* =0.447), stimulus type (F(1,10= 2.333, *p* =0.158), or electrode location (F(2,9)= 3.407, *p* =0.079) for the N100 responses were found. No significant interactions were indicated.

Pillai's trace indicated no significant main effect in the N100–P200 peak-to-peak amplitude for training (F(1,10)= 2.035, *p* =0.184), stimulus type (F(1,10= 5.642, *p* =0.039), but indicated a significant main effect for electrode location (F(2,9)= 73.465, *p* <0.001). Mean amplitudes for N100-P200 recorded from Cz, Tr, and Tl were 2.992, 1.652, and 1.183μV, respectively. Pillai's trace indicated no significant interactions.

Using the Sidak adjustment for multiple comparisons, significant differences were indicated between electrode placements at Cz and Tr (mean difference = 1.340, $p <$ 0.001), and between electrode placements at Cz and Tl (mean difference = 1.808, p <0.001), but not between electrode placements at Tr and Tl.

Pillai's trace indicated no significant main effect for training (F(1,10)= 0.972, p =0.347), stimulus type (F(1,10= 4.455, p =0.061), or electrode location (F(2,9)= 1.808, p =0.219). None of the possible interactions were significant. Pillai's trace indicated no significant main effect in the P200–N200 peak-to-peak amplitude for training (F(1,10)= 3.230, p =0.103), stimulus type (F(1,10= 0.058, p =0.815), or electrode location (F(2,9)= 8.132, p =0.010). Mean amplitudes for P200-N200 recorded from Cz, Tr, and Tl were 1.335, 0.782, and 0.739µV, respectively. No interactions were significant. For the N200 responses to the stimulus with a formant transition onset of 1700 Hz, Pillai's trace indicated no significant main effect in the P200–N200 peak-to-peak amplitude for training (F(1,10)= 0.778, p =0.398), or stimulus type (F(1,10= 0.167, p =0.691), or electrode location (F(2,9)= 6.961 p =0.015). No significant interactions were found.

Correlations Between Behavioral and Electrophysiological Measures

Pearson product-moment correlation coefficients were calculated to establish the relationship between behavioral and electrophysiological measures of perception used in this study. For responses to the stimulus with an onset frequency of 900 Hz, no significant correlations were indicated for percentage of /b/ responses and evoked potentials recorded prior to training at Cz for the P100 latency (r=0.101, p = 0.767), P100-N100 amplitude (r=0.299, *p* = 0.372), N100 latency (r=-0.150, *p* = 0.660), N100-P200 amplitude (r=0.351, *p* = 0.289), P200-N200 amplitude (r=0.360, *p* = 0.276), or N200 latency (r=0.343, *p* = 0.302). A significant correlation was indicated for percentage of /b/ responses and P200 latency (r=-0.351, *p* = 0.290).

For responses to the stimulus with an onset frequency immediately preceding the categorical boundary, no significant correlations were indicated for percentage of /b/ responses and evoked potentials recorded prior to training at Cz for the P100 latency (r=0.069, *p* = 0.840), P100-N100 amplitude (r=-0.045, *p* = 0.895), N100 latency (r=-0.522, *p* = 0.100), N100- P200 amplitude (r=0.093, *p* = 0.785), P200 latency (r=-0.336, *p* = 0.312), P200-N200 amplitude (r=-0.090, *p* = 0.793), or N200 latency (r=-0.259, *p* = 0.442).

In reference to responses to the stimulus with an onset frequency immediately following the categorical boundary, Pearson product-moment correlation coefficients indicated no significant correlations for percentage of /b/ responses and evoked potentials recorded prior to training at Cz for the P100 latency (r=0.002, *p* = 0.994), P100-N100 amplitude (r=-0.122, *p* = 0.720), N100 latency (r=-0.033, *p* = 0.923), N100- P200 amplitude (r=-0.190, *p* = 0.576), P200 latency (r=-0.432, *p* = 0.184), P200-N200 amplitude (r=0.051, *p* = 0.881), or N200 latency (r=0.045, *p* = 0.896).

For responses to the stimulus with an onset frequency 1700 Hz, no significant correlations were indicated for percentage of /b/ responses and evoked potentials recorded prior to training at Cz for the P100 latency (r=0.156, *p* = 0.646), P100-N100 amplitude (r=-0.045, $p = 0.895$), N100 latency (r=0.101, $p = 0.768$), N100- P200 amplitude (r=-0.292, $p = 0.384$), P200 latency (r=-0.464, $p = 0.150$), P200-N200 amplitude (r=0.422, $p = 0.196$), or N200 latency (r=-0.353, $p = 0.287$).

In an effort to find correlations in training effects of behavioral measures and electrophysiological responses, behavioral and electrophysiological difference measures were used. Behavioral difference measures represented the difference in the percentage of /b/ responses from pre-to post-training for the stimuli at the endpoints of the continuum and the stimuli straddling the categorical boundary. Electrophysiological difference measures represented the difference in the recorded latencies and amplitudes for each of the late evoked potential components elicited by the stimuli at the endpoints of the continuum and the stimuli straddling the categorical boundary.

The Pearson product-moment correlation indicated no significant correlation between the difference measures behaviorally and electrophysiologically elicited by the onset frequency of 900 Hz, the onset frequency immediately preceding the categorical boundary, or the onset frequency immediately following the categorical boundary. The Pearson product-moment correlation indicated a significant correlation for behavioral difference measure and difference measure P100-N100 amplitude (r=-0.607, p=0.048), and N100 latency (r=0.640, p=0.043) elicited by the onset frequency of 1700 Hz.

For the group of subjects exhibiting a monotonic function at the initial session, the Pearson product-moment correlation indicated no significant correlation for the behavioral difference measure and difference measure electrophysiological responses elicited by the onset frequency of 900 Hz. A significant correlation for behavioral difference measure and difference measure P200 latency (r=-0.757, *p*=0.049), and N200 latency (r=0.766, *p*=0.045) elicited by the onset frequency immediately preceding the categorical boundary. No significant correlation for the behavioral difference measure and difference measure electrophysiological responses elicited by the onset frequency immediately following the categorical boundary. A significant correlation for behavioral difference measure and difference measure P100 latency (r=0.771, *p*=0.043), and P100-N100 amplitude (r=-0.878, *p*=0.009) elicited by the onset frequency of 1700Hz.

Correlations with Hearing Loss and Age.

Pearson product correlation coefficients indicated a significant (at the 0.05 significance level) negative correlation between the pure tone hearing threshold average (1k, 2k and 4k Hz) and the demonstration of monotonic psychometric functions (r=-0.637, *p* = 0.035). A significant correlation was found between the pure tone hearing threshold average, at 1k and 2k Hz, and the demonstration of monotonic psychometric functions (r=-0.669, *p* = 0.024). Hearing loss was then categorized into flat or sloping loss, with eight of eleven subjects demonstrating a sloping high frequency hearing loss. No significant correlations were indicated for configuration of hearing loss and the demonstration of monotonic psychometric functions (r=-0.463, *p* = 0.152).

No significant correlations were indicated for pure tone hearing threshold average (1k, 2k and 4k Hz) and evoked potentials recorded prior to training at Cz for the P100 latency (r=-0.004, *p* = 0.990), P100-N100 amplitude (r=0.088, *p* = 0.797), N100 latency (r=-0.293, $p = 0.382$), N100- P200 amplitude (r=0.143, $p = 0.674$), P200 latency (r=-0.351, $p = 0.290$), P200-N200 amplitude (r=0.434, $p = 0.182$), or N200 latency (r=-0.300, $p = 0.370$).

Pearson product correlation coefficients did not indicate any significant correlations for pure tone hearing threshold average, at 1k and 2k Hz and evoked potentials recorded prior to training at Cz for the P100 latency (r=-0.042, $p = 0.902$), P100-N100 amplitude (r=-0.088, $p = 0.797$), N100 latency (r=-0.219, $p = 0.518$), N100-P200 amplitude (r=-0.072, $p = 0.834$), P200 latency (r=-0.206, $p = 0.543$), P200-N200 amplitude (r=0.445, $p = 0.170$), or N200 latency (r=-0.342, $p = 0.303$).

No significant correlations were indicated between age and the demonstration of monotonic psychometric functions (r=-0.488, $p = 0.128$). No significant correlations were indicated between age and evoked potentials recorded prior to training at Cz for the P100 latency (r=0.301, $p = 0.369$), P100-N100 amplitude (r=-0.364, $p = 0.271$), N100 latency (r=-0.047, $p = 0.891$), N100- P200 amplitude (r=-0.197, $p = 0.561$), P200 latency (r=0.126, $p = 0.711$), P200-N200 amplitude (r=0.147, $p = 0.667$), or N200 latency (r=0.494, $p = 0.122$).

CHAPTER V
Discussion

General Discussion

The main purpose of this study was to investigate the effect of auditory training on the perception of the formant transition cue in the discrimination of the place of articulation of voiced stop consonants in synthetic CV stimuli of hearing-impaired listeners. Investigation into the use of the formant transition cue included behavioral and electrophysiological measures. Behavioral measures involved a 2AFC method of constants paradigm resulting in psychometric functions and categorical boundary identification, if present, for each participant's perception of the formant transition cue. Electrophysiological measures involved the recording of late auditory evoked potentials from electrode locations Cz, Tr, and Tl. Measurements of perception of the CV stimuli were obtained pre and post training.

Psychometric functions of seven of the eleven participants were monotonic indicating the presence of a categorical boundary. After training, of the seven participants, four demonstrated improvement, two had minimal room for behavioral improvement and one subject appeared to worsen. Of the four participants who did not demonstrate a monotonic psychometric function, three showed no improvement, while one participant appeared to improve after training. Statistical analysis of the behavioral data indicated no significant main effect of training for measures involving the slope of the psychometric function. Also, training was not significant for differences in mean responses from stimuli on one side of the categorical boundary versus the other side of the boundary, as reflected by the height of the psychometric function on each side of the categorical boundary. Electrophysiological measures did not indicate any training effects in pre versus post training responses of P100, N100, P200, N200 absolute latencies or P100-N100, N100-P200, P200-N200 peak-to-peak amplitudes.

A second goal in this investigation was to determine if a transfer of learning took place after auditory training of the formant transition cue. To investigate the generalization of training, listeners were trained using CV stimuli and measures were made of the perception of the formant transition in VC stimuli. Measures of perception used for investigation of generalization included the same behavioral and electrophysiological responses described above. With the exception of one subject, who lacked evidence of categorical perception pre training but exhibited categorical perception post training, there was no clear indication of generalization for the group of subjects in either behavioral or electrophysiological measures.

An additional goal of this study was to document the correlation, if any, between behavioral and electrophysiological responses before, during, and after training. No clear correlations were indicated between behavioral measures, such as the number of /b/ responses at selected points along the continuum of stimuli and electrophysiological measures obtained pre or post training. No significant correlations were found between changes in behavioral and electrophysiological measures from pre to post training. Significant correlations were found between hearing loss, as reflected by pure tone threshold averages, and categorical perception. Age did not significantly correlate with categorical perception. However, all subjects below 55 years demonstrated categorical perception.

Training

It was expected, a priori, that most, or all, of the subjects in this study would improve their perception of the formant transition cue with training. This expectation was based on the results of studies showing improvement in the perception of categorization of stop consonants after training of normal-hearing listeners, improvement of identification of stop consonants after training of hearing-impaired listeners, and improvement of frequency discrimination after training of hearing impaired listeners (Tremblay et al., 2002, Tremblay et al., 2001; Walden et al. 1981).

Behaviorally, improvement in the psychometric functions with training occurred for a few of the subjects indicating that, in some cases, training of the perception of the formant transition cue was successful. Because this improvement was evident in only a few of the subjects, the obvious question of why improvement was seen in some subjects but not other subjects arose. For this reason, the subjects were divided into groups based on hearing loss, configuration of hearing loss, age, and initial, pre-training behavioral performance. Pre-training behavioral performance correlated with hearing loss, as represented by the pure tone threshold average. Pre-training behavioral performance did not correlate with the configuration of the hearing loss or age. Correlation results indicated that subjects with more severe hearing loss are less likely to demonstrate categorical perception. Excluding the two subjects with minimal room for improvement, all but one of the subjects who demonstrated categorical perception during the pre-training session, improved after training. It may be inferred that the severity of hearing loss indicated which subjects could demonstrate categorical perception, and those subjects were more likely to improve after training. However, no significant main effect for training among subjects with initial functions was found. However, a larger sample size may have resulted in significance.

Electrophysiological measures did not indicate a change in perception due to training. Training had no significant effect on the P100, N100, P200, N200 latencies, or the P100-N100, N100- P200, P200-N200 amplitudes. No significant main effects for training were noted after the subjects were divided into groups according to hearing loss, configuration of hearing loss, age or presence of initial functions.

There are many possible reasons why behavioral and electrophysiological improvement with training was not observed in all of the subjects. The break-down in signal processing may have occurred anywhere along the auditory pathway from the cochlea to the cortex. A possible reason why improvement was not observed in some of the subjects, especially subjects not able to demonstrate categorical perception, may be due to the coding of the stimuli at the level of the auditory nerve. According to Willott (1991), age and hearing impairment reduced the number of 8th nerve fibers. Further, in research involving aging gerbils, compound action potentials were reduced in amplitude, while average single fiber discharge rates at the level of the auditory nerve remained the same (Hellstrom and Schmiedt, 1990). Willott (1991) suggested that this decrease in action potential amplitude could be the result of a reduction in the single fiber phase-locking ability. Measurements at the level of the auditory nerve reflect some of the processing of speech stimuli in the average discharge rate and the synchrony of discharge, or phase-locked firings of single fibers of the auditory nerve (For review, see Eggermont, 2001). The average discharge rate has been used as a tool to reflect components of the speech signal such as steady-state vowel information and formant transitions.

The means by which formant transitions are coded is best represented the phase-locking ability of the nerve. The rate-place theory suggests that auditory nerve fibers act as a cohesive group of filters when processing auditory information. In the rate-place model, the change in the number of discharges from the fibers represents the spectral peaks of the stimuli and can indicate changes to the formants of the signal presented over time. Measurement of the phase-locking ability of the auditory nerve may give more information about the processing of spectral information of the CV stimuli than the average discharge rate. It is common for the number of discharges recorded from a fiber to be displayed graphically in a histogram as a function of time. Eggermont (2001) states that the largest peak in a post stimulus time histogram reflects the dominant response of that auditory nerve fiber. Formant transitions can be estimated from the changes in the dominant response of groups of nerve fibers over a period of time.

The processing of formant transitions differs from processing temporal cues. In contrast to Tremblay et al. (2001), who focused on the effects of training on perception of VOT, the present study focused on the effects of training on perception of the formant transition cue. The discrimination of a voiced stop consonant versus a voiceless stop consonant depends on differences in the processing of temporal information. According to Sinex and McDonald (1989), temporal processing is reflected in both average discharge rate and phase-locking ability. In examining the signal processing of VOT, between voiced and voiceless stop consonants, reflected by both average discharge rate and phase-locking ability, there was no difference found between the two methods of measurement. However, processing of the voiced stop consonants using the formant transition cue is better represented by the phase-locking ability of the auditory nerve than the average discharge rate of that same fiber.

The ability of the auditory nerve to represent formant transitions via phase-locking is impaired with damage to the nerve. Damage or acoustic trauma to the auditory nerve can result in degradation of phase-locking ability. This degrading of phase-locking ability results in a diminished ability to process speech stimuli (Miller, Schilling, Franck, and Young, 1997). Miller et al. found that sensorineural hearing loss in cats resulted in the inability of the auditory nerve fibers to fire with the same degree of synchrony as fibers from a cat with a normal auditory system. In the normal system, the synchronized rate of auditory nerve firings reflects the formants of the synthetic vowel stimuli with little internal noise or synchronized firings at frequency regions other than that of the formants. In the damaged auditory system, the synchronized rate of auditory nerve firings reflects more internal noise and does not represent or capture the formants of the synthetic vowel stimuli. It was speculated by Miller et al. that damage to the periphery of the auditory system causes degradation of the temporal processing and the difficulty in identification of speech stimuli.

Previous research has indicated the association between degraded phase-locking and impaired perception of formant transitions. Plyler and Ananthanarayan (2001) suggested that the degradation of the phase-locking ability of the auditory nerve may account for difficulty in the identification of voiced stop consonants by all but a few of the hearing-impaired listeners in their study. Along with the difference between hearing-impaired and normal-hearing listeners in behavioral measures, poor representation of the formant transition in an electrophysiological measure was reported. The frequency following response reflected the formant transitions of the stimuli in normal-hearing listeners. However, representations of the formant transition were not well represented by the frequency following response in hearing-impaired listeners. It was concluded that the degraded phase-locking ability might be the reason for both behavioral and electrophysiological findings.

To summarize, the phase-locking ability of the auditory nerve is an important factor in neural representation of the dynamic spectral information of the formant transition. Impairment and degradation of phase-locking ability is related to hearing loss. The lack of phase-locking ability results in the inability to identify or capture parts of the speech signal (Miller et al., 1997). As Plyler and Ananthanarayan (2001) had suggested, the diminution of the phase-locking ability may be the physiological source of difficulty in the identification of stop consonants by hearing-impaired listeners. This would explain the difficulty of four of the participants in the present study to categorize the stop consonants. The inability to train listeners with impaired phase-locking, at the level of the 8^{th} nerve, is supported by research in the area of auditory plasticity. Not all regions of the auditory system exhibit the same degree of plasticity. Auditory functions at subcortical levels are less plastic than those processed cortically (Willott, 1996). Thus, it is not surprising to consider that some of the participants, possibly with degraded phase-locking ability of the eighth nerve, would not show improvement with training.

Generalization

The literature indicates that a transfer of learning can take place from the stimuli used in auditory training to similar stimuli (Tremblay et al., 1997). The behavioral responses in the present study indicated a lack of categorical perception obtained during pre- and post-training sessions from all but two of the participants. No improvement was observed for these two participants (subjects 3 and 5). The other nine participants failed to demonstrate pre training categorical perception.

The reason for the lack of categorical perception to VC stimuli of the participants in this study is unknown. Categorical perception of VC stimuli is affected by acoustic cues other than the formant transition, such as the silence preceding the burst, known as the stop gap, or the burst component. These cues may carry more perceptual weight in

VC stimuli than CV stimuli. However, it is unlikely that the use of other acoustic cues is the cause for the lack of categorization by the participants because the burst component and the stop gap are optional for stop consonants in the final position (for review see Kent, Dembowski, and Lass, 1996). Sher and Owens (1974) reported that the probability of error in the identification of both the /b/ and /d/ phoneme is greater in CV stimuli than VC stimuli. This finding is inconsistent with the results of this study. In this study, the participants were able to categorize CV stimuli more readily than VC stimuli. Additionally, Collins (1984) found that difference limens for frequency glides were larger for glides preceding the steady-state portion of synthetic CV stimuli than glides following the steady-state portion of synthetic VC stimuli for normal hearing listeners suggesting that discrimination was more difficult for CV than VC stimuli. This effect in difference limens was not consistent among hearing-impaired listeners but the results, in general, are inconsistent with those reported in the current study.

For the present study, the generalization of training effects of VC stimuli was contingent upon successful training in the perception of the CV (experimental) stimuli. Training had an effect on the responses to the experimental stimuli of the subjects with initial functions. Yet, only two of the subjects demonstrated an initial function to the generalization stimuli. Therefore, it is difficult to conclude with confidence whether generalization occurred. However, it was observed that one subject did not exhibit a monotonic function at the initial session, but exhibited monotonicity, meeting the 70%

and 30% /b/ response criteria after training (subject 10). Subject 10 did not show any training effect on the experimental stimuli due to a ceiling effect.

While the reason for the lack of training and generalization is not clear, results from this study regarding training and generalization effects likely differed from results of Tremblay et al. (1997) due to differences in subject pools. The Tremblay et al. study employed normal-hearing listeners,between the ages of 21 and 31 years, in a task of training to discriminate a non-English temporal cue related to VOT. Interestingly, for the group of subjects, this training generalized into better use of a non-English temporal cue related to formant transition. Subjects in the present study were older with poorer hearing sensitivity than the subjects in the Tremblay et al. study. As previously stated, lack of training and generalization effects may result from degraded phase-locking abilities of the 8th nerve due to hearing loss or aging. It is possible that this degradation affects the processing of transitions in the final position more than transitions in the initial position. Additionally, forward masking of the transition in the final position by the vowel portion of the stimulus may have occurred. Forward masking could cause greater difficulty in the perception of the formant transition in the final position than the perception of the formant transition in the initial position.

Correlations

Both behavioral and electrophysiological measures have been used to represent the processing of speech by the auditory system (Kraus et al., 1993; Kraus et al., 1995; Plyler and Ananthanarayan, 2001; Tremblay et al. 1997; Tremblay et al., 2001; Tremblay et al. 2002). The results from the present study prove that it is difficult to correlate results from the two areas of measurement. Of the 28 correlations investigated between pre training behavioral and electrophysiological measures from Cz, only one correlation was found to be significant (percent /b/ and P200 latency response to onset frequency of 900 Hz.).

No method of correlation between the behavioral and electrophysiological data in this study provided consistent results. One reason may be due to the difficulty in quantifying individual behavioral performance. The slope of the psychometric function, the categorical boundary, and the height from one point to another have all been used. However, in this study, no one measure best represented the psychometric function of every subject. Additionally, some measures, such as slope, could not be computed for some psychometric functions and therefore could not be used as a method of comparison between all subjects.

If a method of limits using an up-down procedure was used to estimate the minimum frequency range within which a listener can discriminate between two speech-sounds, it may reflect the perception of the formant transition cue in a more quantitative manner. Additional information about the same process may be of value in making comparisons with electrophysiological measures.

It is also possible that the electrophysiological measures and the behavioral measures did not reflect the same levels of auditory processing of the formant transition cue. While behavioral measures encompass higher and lower levels of auditory system, the electrophysiological measures implemented in this study reflect processing of the central auditory system. While the processing of dynamic spectral information, such as phase-locking, at the level of the auditory nerve precedes central processes, changes in the phase-locking ability of the auditory nerve do not necessarily affect measures reflecting central processes.

Methodology

Training Paradigm.

The method of training used in this study reflected the method of training reported in a study by Tremblay et al. (2001). In this method of constants procedure, the listener was presented with stimuli in a random order. After indicating which sound was heard, the listener was provided feedback in the form of a flash of green light for each response that was consistent with the listener's original perceptual response as reflected by the psychometric function. The method provided an interactive process that kept the listeners' attention and it proved to be effective in altering the psychometric functions of most of the participants who had recordable psychometric functions at the initial test session. Of the seven subjects that had monotonic functions with at least 70% of the responses /b/ on one side of the categorical boundary and at most 30% of the responses /d/ on the other side of the categorical boundary, four subjects improved, two subjects had no room for improvement, and one appeared to worsen. Of the four subjects who did not exhibit a monotonic function at the initial session, three subjects showed no improvement while one subject was able to demonstrate categorical perception only after training.

In retrospect, it is possible that the training procedure used in this study, the method of constants procedure, is sufficient for training on only two stimuli, (Tremblay et al., 2001), but may not be the best method of training listeners to multiple stimuli. The method of constants allows for repeated exposure to all of the stimuli in the continuum and presents each stimulus an equal number of times. Therefore, this method allows for an equal amount of time spent on each stimulus during the training process. Because most of the subjects in the study who exhibited a monotonic function and some of the subjects who did not exhibit such a function needed very little, if any, improvement near the endpoints of the continuum, time spent training these listeners on stimuli at or near the endpoints may be better spent on stimuli near the categorical boundary where there was room for improvement.

Training that provides for more practice at the point at which the listener has more difficulty differentiating between the perception of the /b/ sound and the /d/ sound would likely be more efficient and possibly more effective. A method of limits using an adaptive up-down technique described by Levitt (1971), used in psychoacoustics to determine differential thresholds, could be implemented. An adaptive procedure in which one level of discrimination ability is required before continuing to the next, more difficult level likely would be a more time efficient method and may have more effect on learner outcome. Instead of presenting the listener with random stimuli from the continuum of stimuli, the furthest two points, equidistance from the categorical boundary would be presented to the listener in a same-different paradigm. If the response was correct, the next pair of stimuli equidistance from the categorical boundary but a step closer to the boundary in the continuum would be used. This process would continue in a two-down, one-up manner until the 71% correct level is established and a range of frequencies in which the listener cannot discriminate one from the other would result (Levitt, 1971).

The method of limits using an adaptive up-down technique would allow for more presentations of stimuli in the frequency range where the listener demonstrates the most difficulty in discriminating and the greatest need for training. However, this method prevents the presentation of stimuli at or near the categorical boundary for listeners who are not able to proceed to that point in the training. Possibly, a method of constants technique could be used for the stimuli that are within the range that is beyond the listener's ability to discriminate.

Behavioral Measures. One area of consideration in this study is the method in which data was obtained. Behaviorally, examination of psychometric functions does not allow much opportunity for investigation into the processing of speech-stimuli or changes in those processes. The method of constants procedure employed in this study provides information on the listener's perception of the stimuli but is limited to changes in the slope or descriptions about the shape of the function. The method does not allow for responses to be interpreted as correct or incorrect. Therefore, the method does not allow for use of detection theory measures, such as d', or P(c).

An adaptive method, such as an up-down method of limits using paired stimuli in a same-different task may be more advantageous. Data from such a task may result in the ability to quantify levels or ranges of frequencies that the discrimination ability of the listener begins to degrade. It may be of value to record the perception of the listener with both the method of constants and an up-down method of limits.

Electrophysiological Measures. Another area in the present study that warrants consideration is the method of obtaining electrophysiological data. While electrophysiological measures are objective, variability is an issue. Between subjects variability in the electrophysiological measures was likely a factor in many of the statistical analyses indicating lack of significance. Standard deviations were large for latency and amplitude measures. For example, the mean peak-to-peak amplitude for the N100-P200 response, recorded at Cz, to the onset frequency of the stimuli immediately before the categorical boundary ranged from 2.3-3.3μV, with the standard deviations ranging from 0.68-1.56. However, Anderer et al. (1996) reported standard deviations similar to those measured in the present study, and found significant effects. For example, Anderer et al. reported the mean amplitude for the N100-P200 response as 4.8μV, with the standard deviation of 2.0. The response was recorded at Cz from twelve subjects, 70-79 year of age.

Additionally, it was observed that a few of the electrophysiological responses were very noisy. The noisy response makes recording procedures difficult, as well as interpretation of waveforms. Because an electromagnetically shielded booth was employed, the origin of the noise was likely internal. This may reflect the excessive internal noise, which results in a poorer signal-to-noise ratio in the degraded phase-locked response, discussed by Miller et al.(1997).

As mentioned in the previous chapter, the P100 and N200 waves were not identifiable in some of the electrophysiological responses for some of the stimuli. It is not clear as to why the waveforms were absent or difficult to identify. There are a few possible factors that may have contributed to these missing responses. Excessive noise in the response signal, as previously mentioned, has an affect on the interpretation of the waveforms and identification of the waveform components. It is possible that small amplitude waves were masked by noise in the response signal. The severity of hearing loss may also contribute to the absent responses. As stated previously, there may be a connection between severity of hearing loss and categorical perception. There may also be a connection between categorical perception and degraded phase-locking ability.

Another possible factor contributing to the missing responses is advanced age. However, the number of absent or difficult to identify waveforms for those subjects over 55 years accounts for just over 51% of the absent or difficult to identify responses. There is little information in the literature about the effects of advancing age on the P100 response. Age is not a significant factor in P100 amplitude in the processing of VOT cues (Tremblay, Piskosz, and Souza, 2003). It has been shown that the N100, P200, N200, and P300 are affected by advancing age. The N100 amplitude increases with advancing age, while the amplitude of the P200 response increases until approximately

60 years of age before beginning to decrease. The amplitude of the N200 response decreases in amplitude with advanced aging (Anderer, Semlitsch, and Saletu, 1996). While advanced age may have had an effect on the electrophysiological measures performed in this study, lack of conclusive evidence obtained in this study prohibits any confident inferences.

As previously stated, an imputation process was performed to complete the data set for statistical analysis. Analysis of variance of the data could not be performed with missing data points. Imputation allowed for the completion of the data set while minimally affecting statistical analysis. Statistical analysis indicated no significant results related to the P100 and N200 latencies conclusions were made using the measures that underwent the imputation process.

Electrode Location. Location of the electrodes used in recording the electrophysiological responses was found to be significant for many of the responses measured. The largest peak-to-peak amplitudes were consistently measured from Cz. For each case in which electrode location was found to be a significant main effect, post hoc pair-wise comparisons indicated that amplitudes measured at Cz were larger than those at Tr and/or Tl. Any difference in changes of electrophysiological responses recorded over the left versus the right hemisphere was of interest in this study. There have been reports of hemispheric asymmetry after training similar to the training implemented in this study (Tremblay et al., 2002). In an effort to investigate asymmetric responses or asymmetric changes in responses after training, post hoc pair-wise comparisons were performed. None of the pair-wise comparisons for electrode location indicated a significant difference between responses recorded at Tr versus Tl. The age of the subjects may be a factor in this finding. It has been shown that long latency auditory evoked responses are less likely to show asymmetries in the processing of speech sounds in the elderly population (Bellis et al., 2000).

Another possible reason why no hemispheric asymmetries were recorded was the location of the electrodes. While electrodes located over Tr and Tl are consistent with the results presented in the Tremblay et al. (2001) study, the Tremblay et al. (2002) study reported measuring hemispheric asymmetry from electrodes over the frontal lobe (Fr and Fl). Use of additional electrodes for the frontal lobe or electrodes over the frontal lobe in place of electrodes over the temporal lobe may have resulted in the recording of asymmetry.

Future Research

The change in psychometric functions after training for listeners who had initial functions is encouraging. Replication of this study using an adaptive behavioral up-down method of limits in conjunction with a method of constants with paired stimuli may provide additional insight into listener perception of formant transitions. Electrophysiological measures using an oddball paradigm, such as MMN and the P300 response would give a different view of the representation of the physiological side of the listener’s discrimination ability.

Another possible research plan may include measuring the perceptual abilities of frequency glides of young normal-hearing listeners. If phase-locking abilities degrade at higher frequencies, then young, normal-hearing listeners should have difficulty discriminating between two glides at high frequencies. Initially, listeners would perform a 2AFC task that would reflect discrimination abilities. The use of both a method of constants and a method of limits procedure may be employed. Electrophysiological measures, such as FFRs, late evoked potentials, and event-related potentials may be implemented following behavioral measures.

Investigations involving young, hearing-impaired listeners may allow for control of possible confounding age effects. Future research may also involve elderly normal-hearing listeners to control for possible hearing loss effects. Further research may look into the reason why some subjects demonstrate categorical perception and improve with training while other subjects within the same age group or with the same degree of hearing loss are unable to demonstrate categorical perception or improve with training.

Clinical Application

The information in this study contributes to the knowledge of the ability of the human auditory system to process the formant transition cue. Some hearing-impaired listeners demonstrated the ability to perceive categories using this cue, while other listeners could not. It should be noted that most of the listeners with good categorical perception were younger adults in this study. The listeners with categorical perception have a greater likelihood of modifying or improving this categorical perception with training. Therefore, some form of auditory training may be of use to these listeners. However, the type and amount of training cannot be determined at this time. More research involving the training of listeners with some degree of categorical perception must be accomplished before further speculation is made. It is not known if the listeners with some categorical perception need to improve the perception of the formant transition to improve listening in everyday situations. For the listeners who could not demonstrate categorical perception, it may be possible that hearing aid algorithms be designed to enhance the formant transition. Extra amplification and enhancement of the formant transition may improve the internal signal-to-noise ratio in the phase-locking process.

Conclusions

1) Some hearing-impaired listeners can be trained to improve the perception of formant transitions.
2) The probability of successful training likely depends on the listener's categorical perception of the formant transition cue prior to training. The severity of hearing loss and age of the listener may have also contributed.
3) Listeners without the ability to categorize stimuli by use of the formant transition cue have little likelihood of improving categorical perception through auditory training.
4) Generalization did not take place in the form of improved categorical perception of the formant transition in VC stimuli following auditory training.

5) No successful correlations between behavioral and electrophysiological measures were achieved using the methods implemented in this study.

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APPENDICES

APPENDIX A

Table 1. Subject age, sex, hearing sensitivity, and use of hearing aids.

Subject	Age (yr)	Sex	250 Hz (dB HL)	500 Hz (dB HL)	1000 Hz (dB HL)	2000 Hz (dB HL)	4000 Hz (dB HL)	8000 Hz (dB HL)	H.A.Use
1	72	Male	25	40	45	45	45	45	Yes
2	44	Male	30	35	50	55	60	45	Yes
3	66	Male	30	20	35	35	60	65	Yes
4	65	Female	30	40	55	60	60	55	Yes
5	23	Male	10	30	35	35	55	65	No
6	70	Female	15	30	50	55	45	40	Yes
7	71	Male	15	25	45	55	55	60	Yes
8	58	Male	30	35	40	60	60	60	Yes
9	44	Female	40	35	45	45	35	20	Yes
10	45	Female	45	45	40	45	40	30	Yes
11	63	Male	20	30	40	50	65	50	No

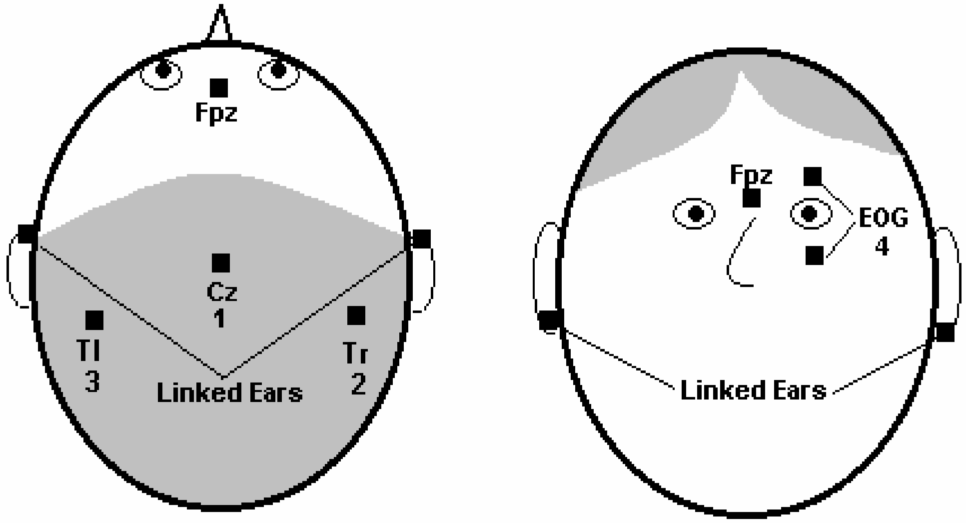

Figure 1. Electrode location for auditory evoked potentials. Auditory elicited responses were recorded from electrodes placed at Cz, Tr, and Tl. Linked earlobes were used as a reference, while Fpz was used as a ground. Eye blinks (EOG) were measured from above and below the left eye.

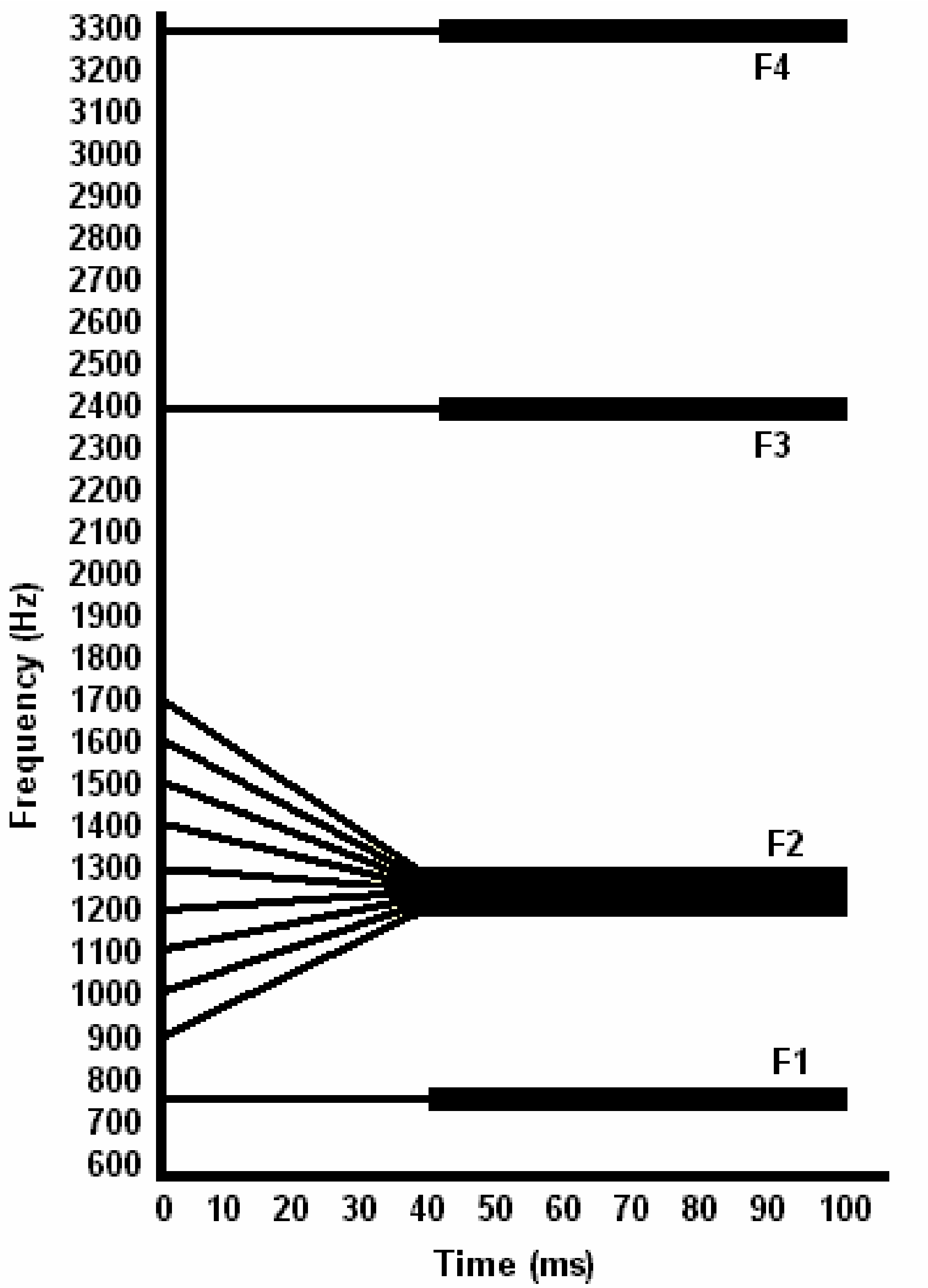

Figure 2. Synthetically generated stimuli. Onset frequency of formant transitions varied along a continuum in 100 Hz steps from 900 Hz to 1700 Hz.

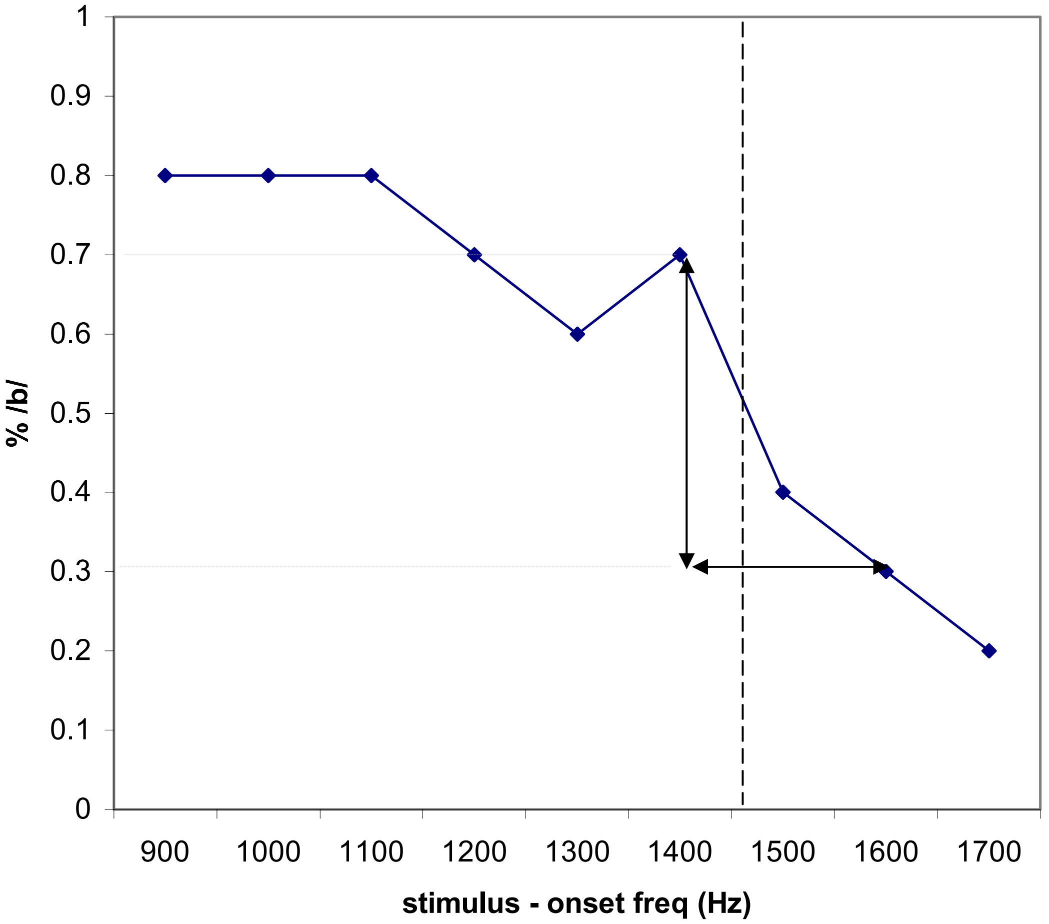

Figure 3. Calculation of the slope of a psychometric function. The data points used in the slope calculation include the point immediately preceding the boundary with at least 70% /b/ response and the point immediately following the boundary with at most 30% /b/ response. The change in height is divided by the change in horizontal distance between the two points.

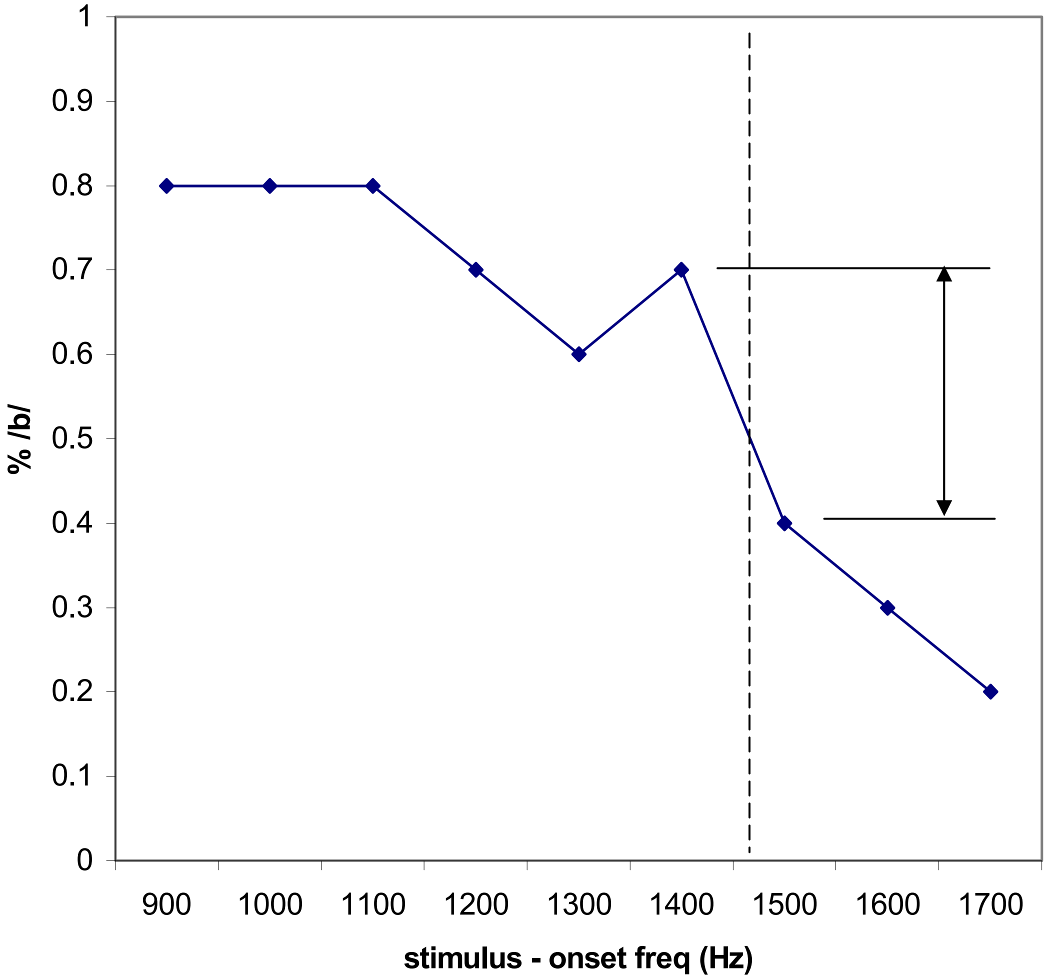

Figure 4. The calculation of the difference in height between two parts of a psychometric function. The difference in height is the vertical distance between the point immediately preceding the boundary and the point immediately following the boundary. Unlike the data points used to calculate slope, these data points do not have to be at least 70% or at most 30% /b/.

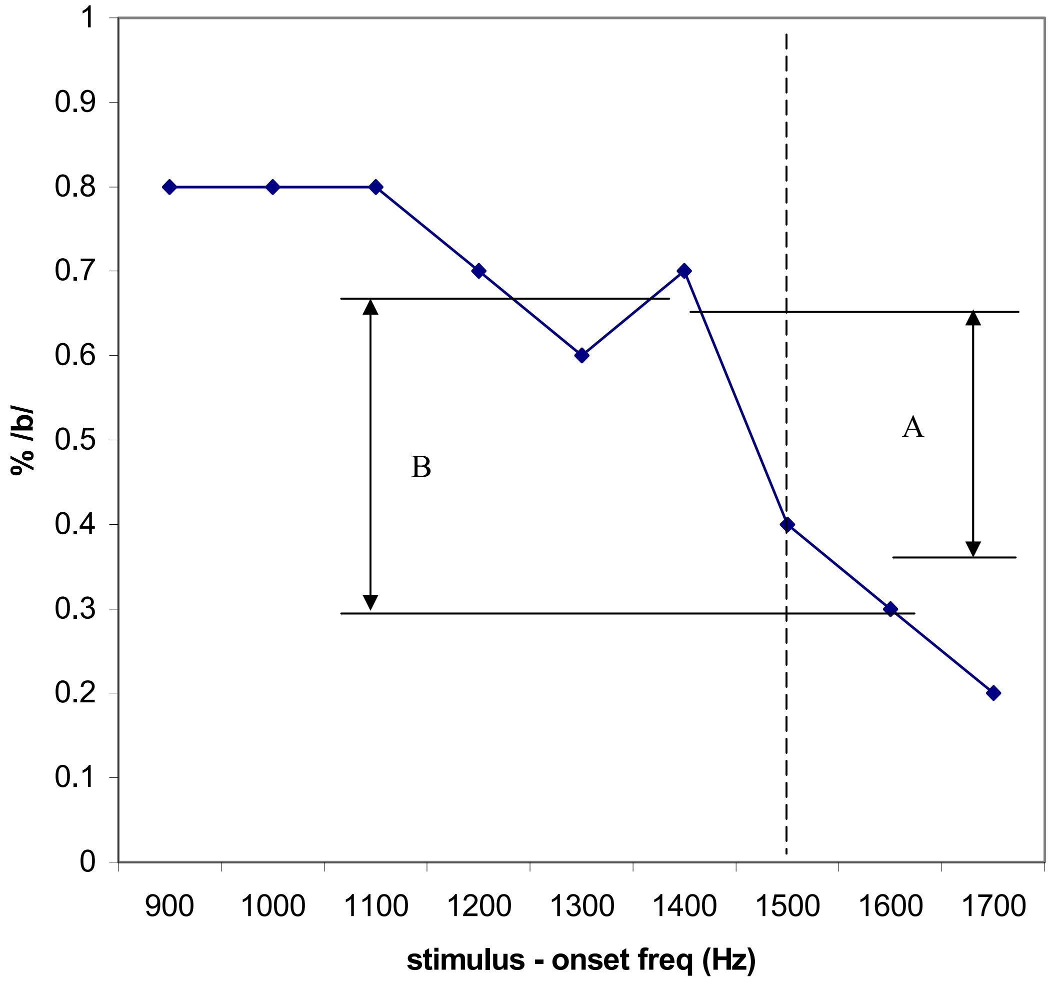

Figure 5. The calculation of the difference in height between two parts of a psychometric function using two (A) and three (B) points on each side of the boundary. The difference in height is the vertical distance between the mean height of the points preceding and following the boundary. Data points do not have to be at least 70% or at most 30% /b/.

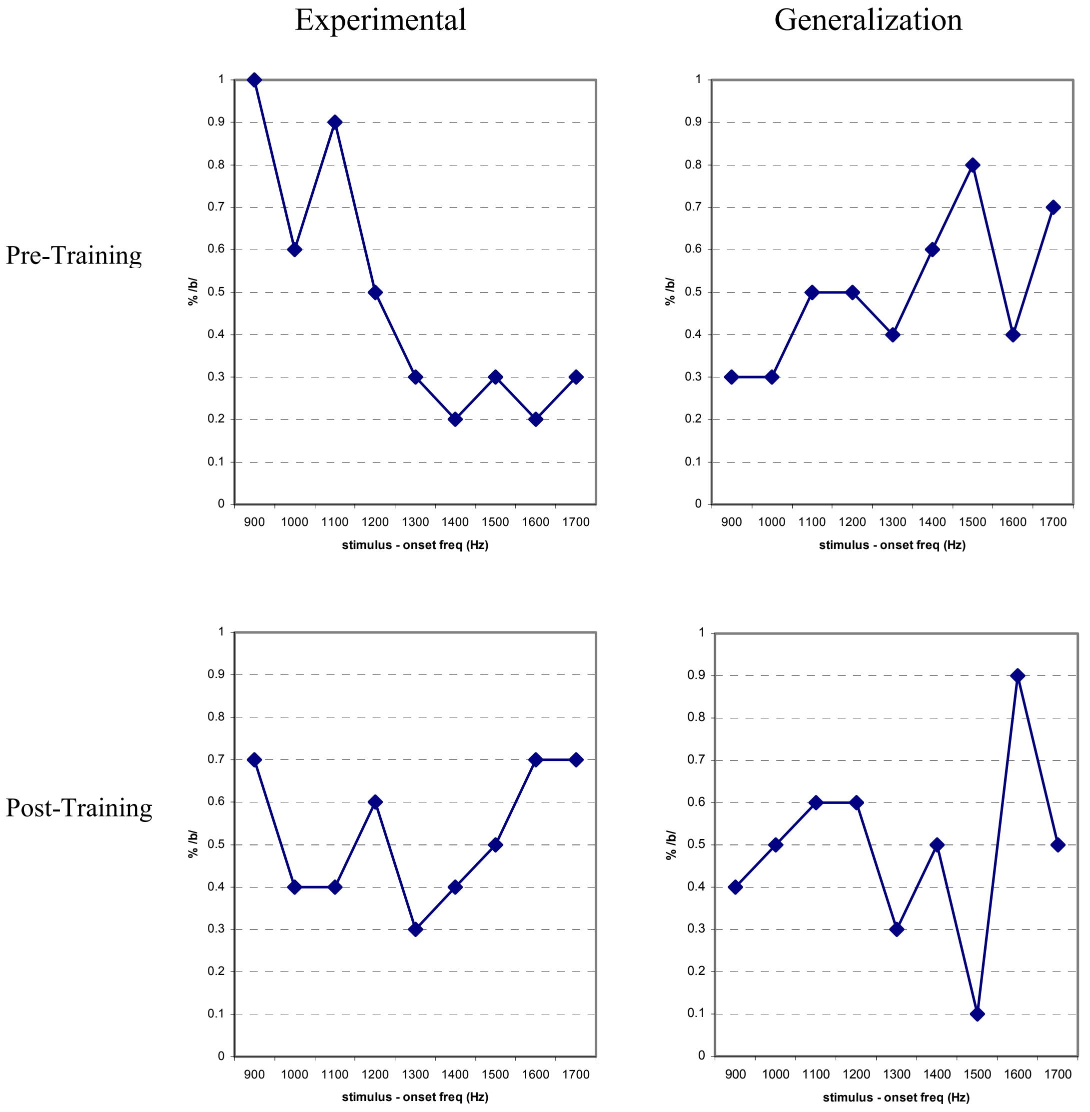

Figure 6. Pre and post training psychometric functions of responses to the experimental and the generalization stimuli for subject 1.

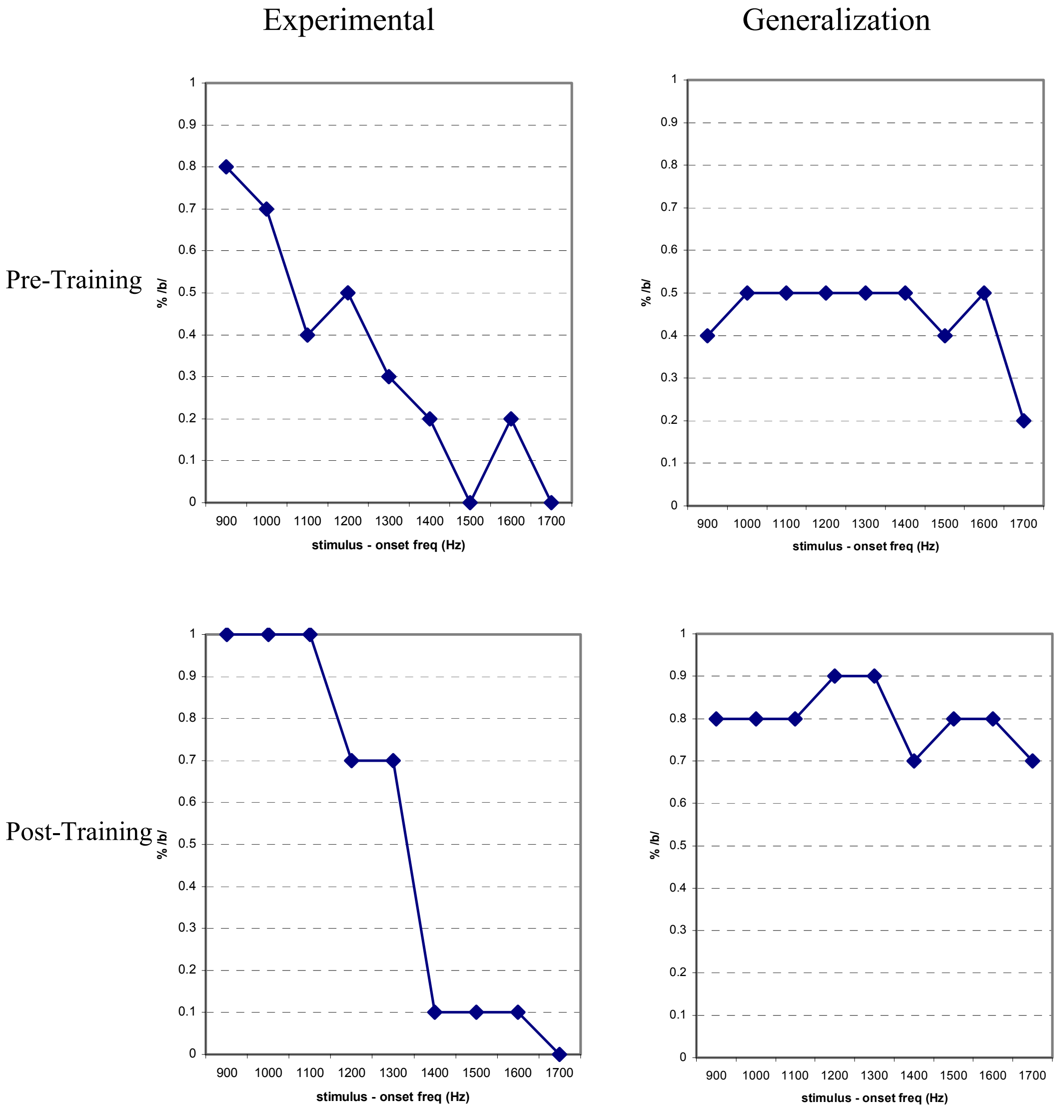

Figure 7. Pre and post training psychometric functions of responses to the experimental and the generalization stimuli for subject 2.

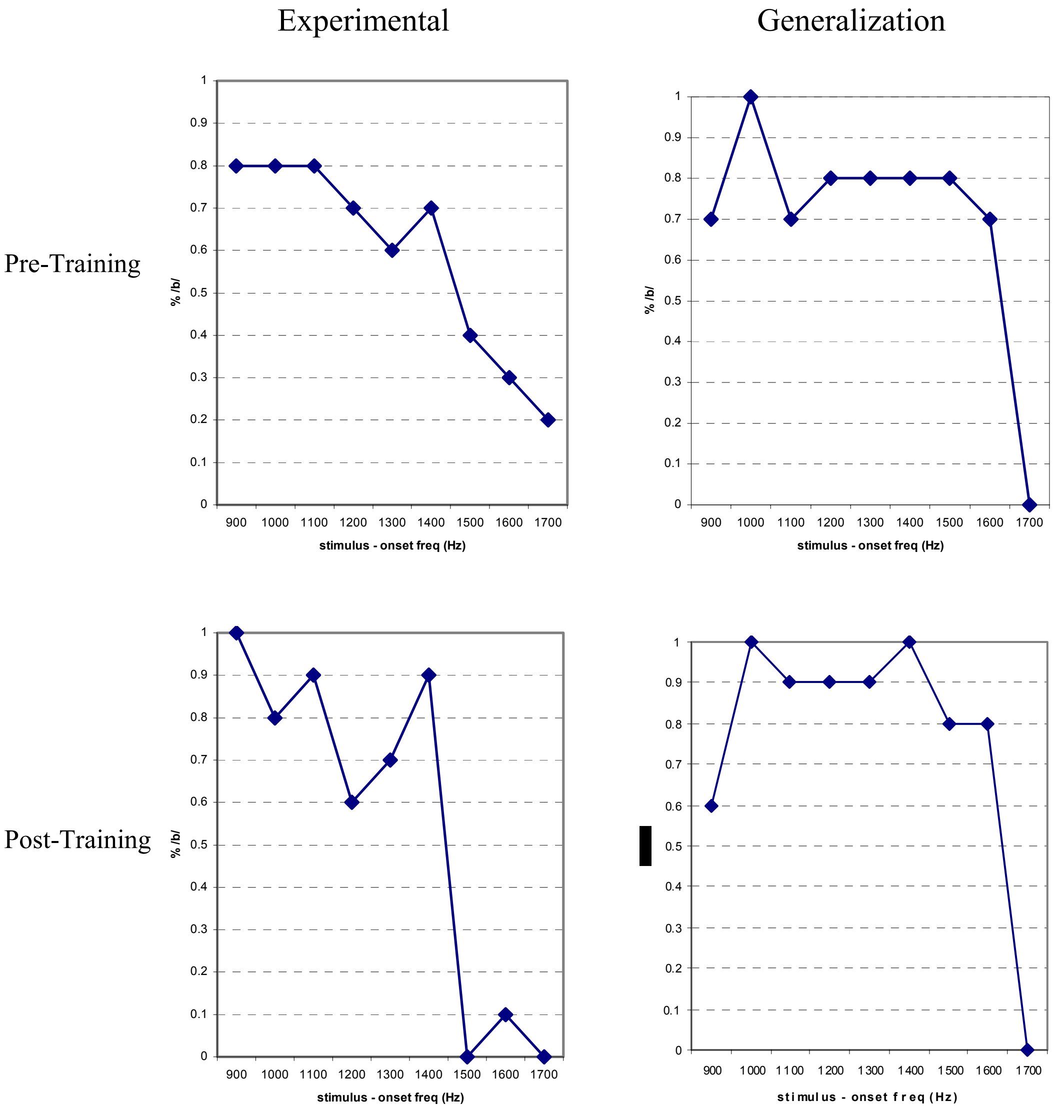

Figure 8. Pre and post training psychometric functions of responses to the experimental and the generalization stimuli for subject 3.

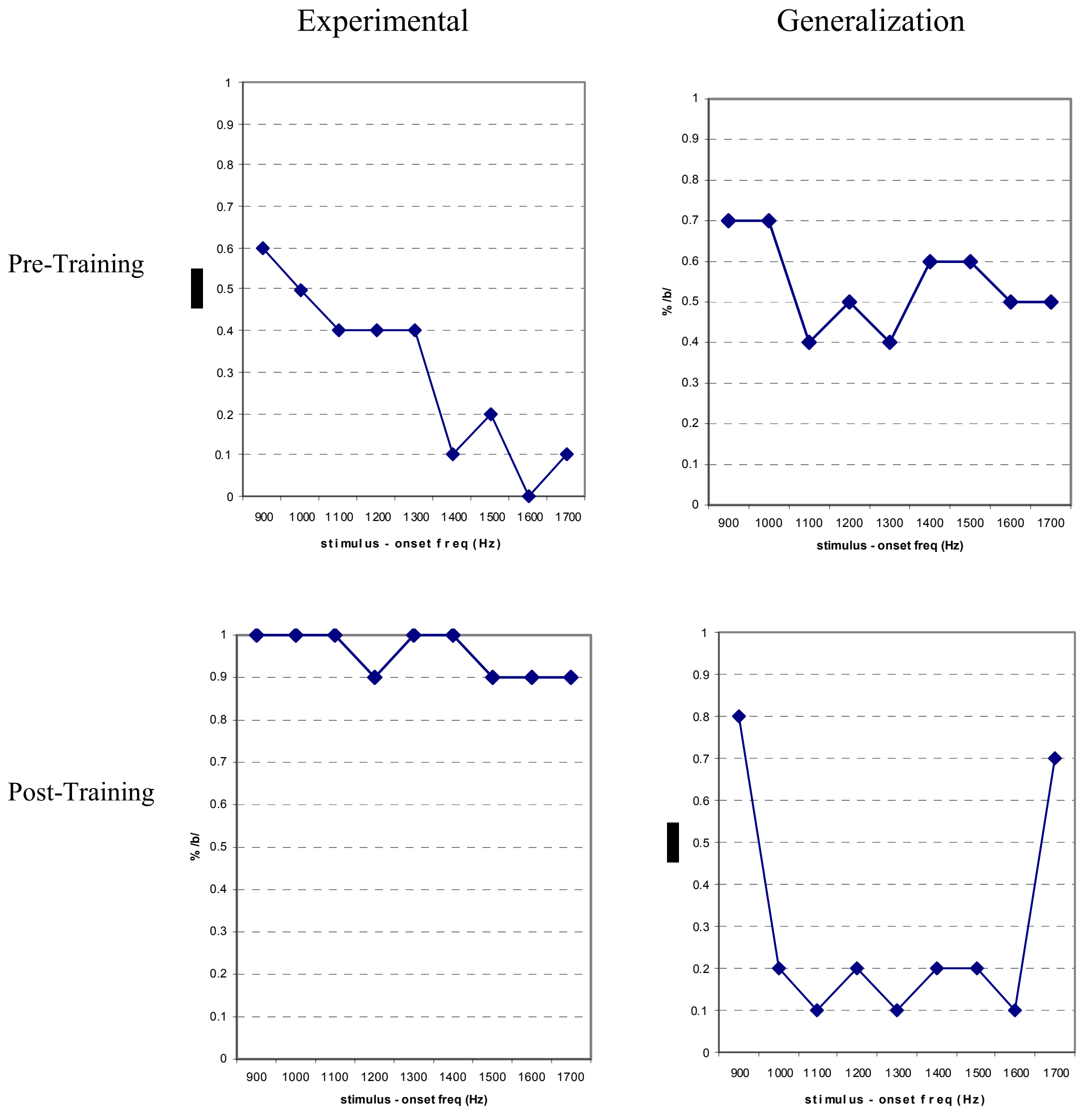

Figure 9. Pre and post training psychometric functions of responses to the experimental and the generalization stimuli for subject 4.

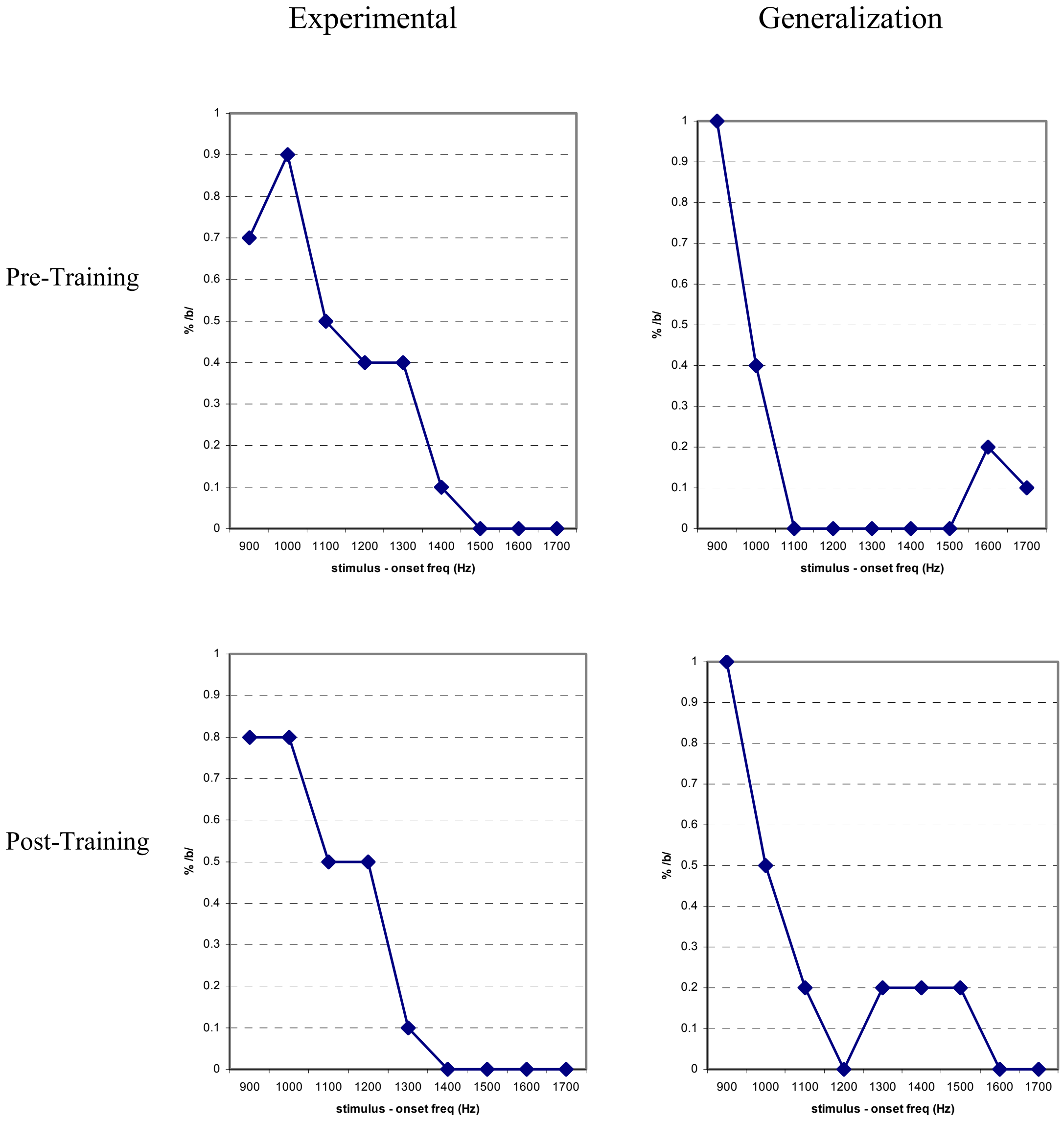

Figure 10. Pre and post training psychometric functions of responses to the experimental and the generalization stimuli for subject 5.

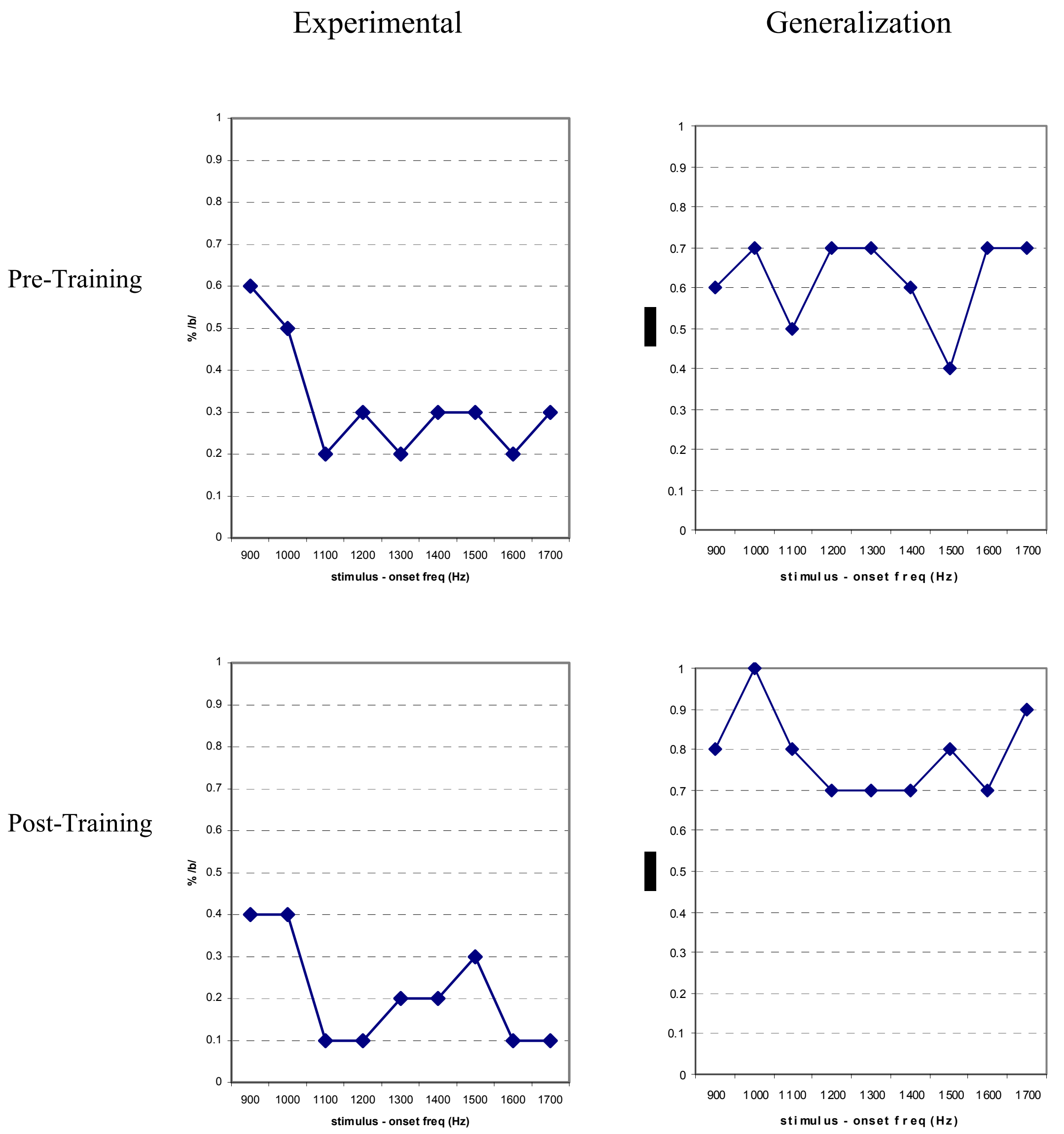

Figure 11. Pre and post training psychometric functions of responses to the experimental and the generalization stimuli for subject 6.

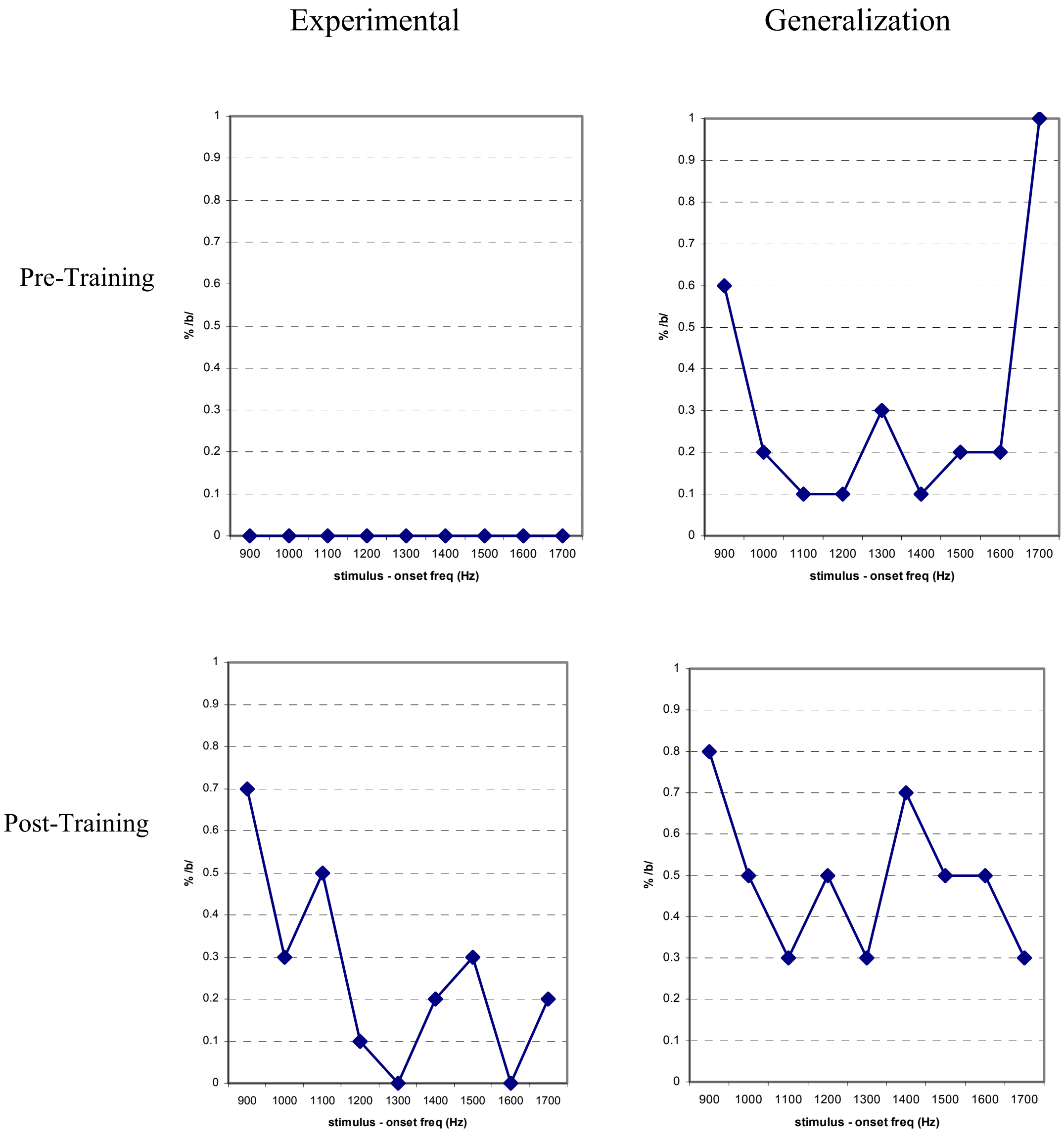

Figure 12. Pre and post training psychometric functions of responses to the experimental and the generalization stimuli for subject 7.

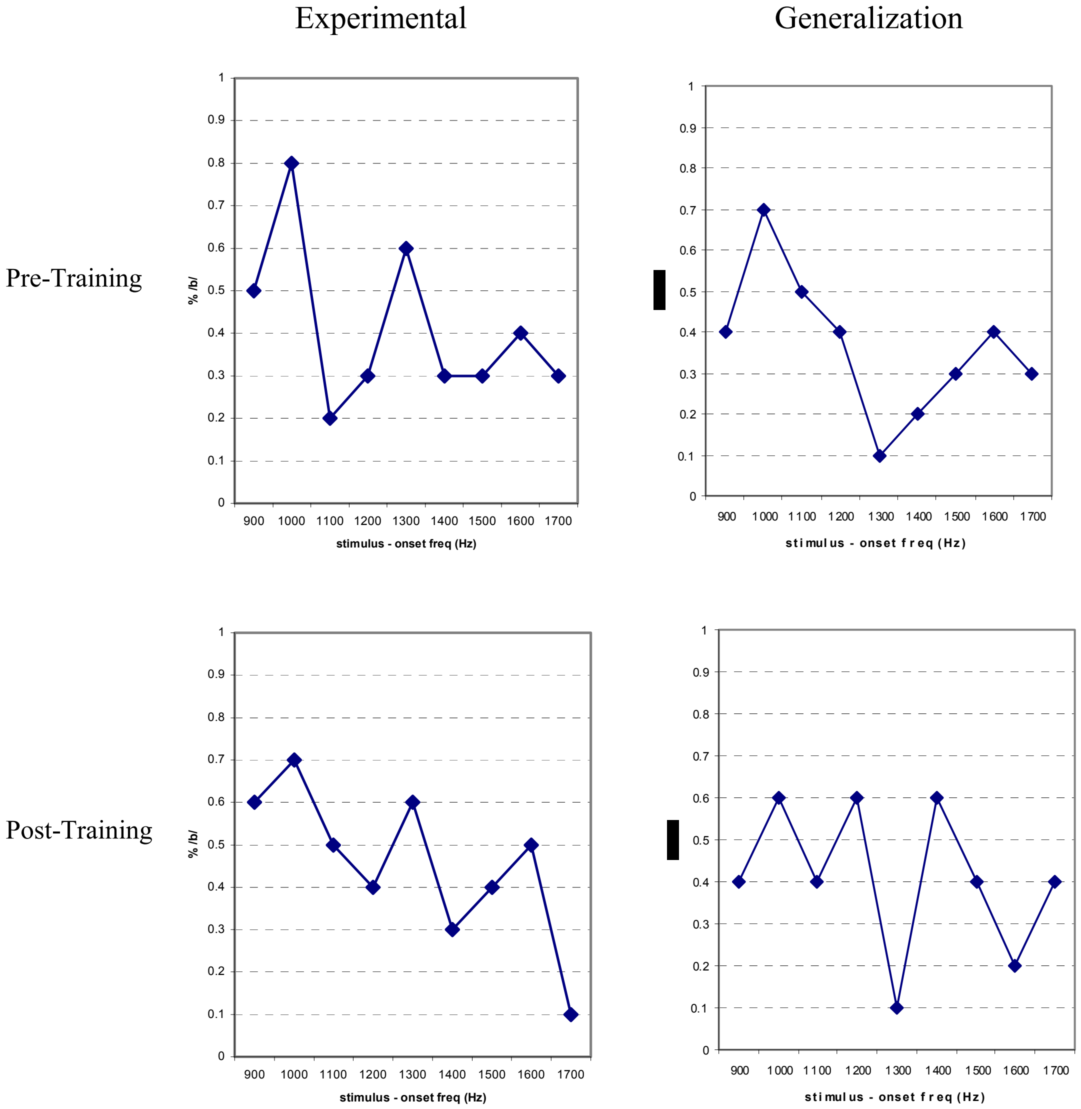

Figure 13. Pre and post training psychometric functions of responses to the experimental and the generalization stimuli for subject 8.

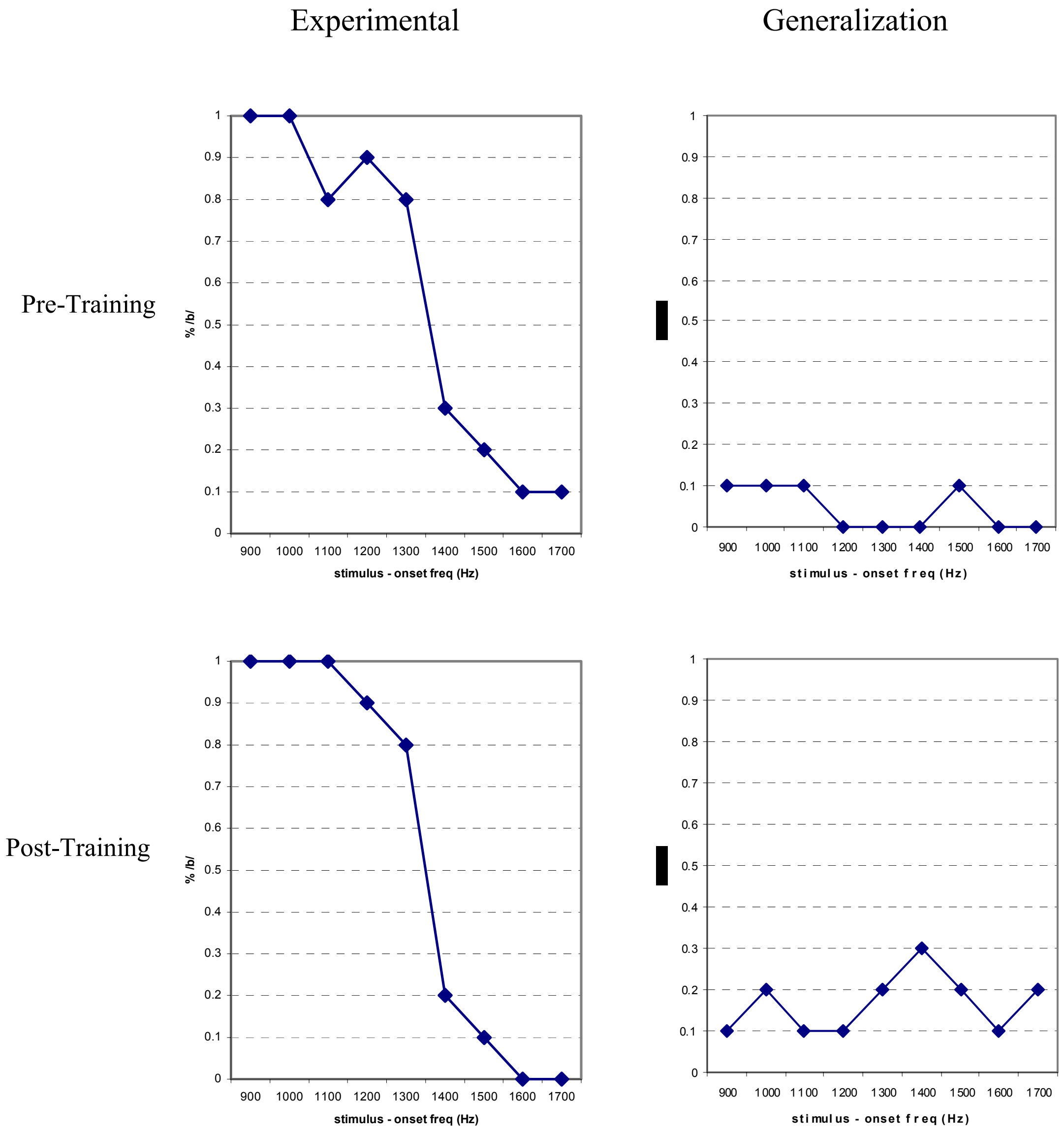

Figure 14. Pre and post training psychometric functions of responses to the experimental and the generalization stimuli for subject 9.

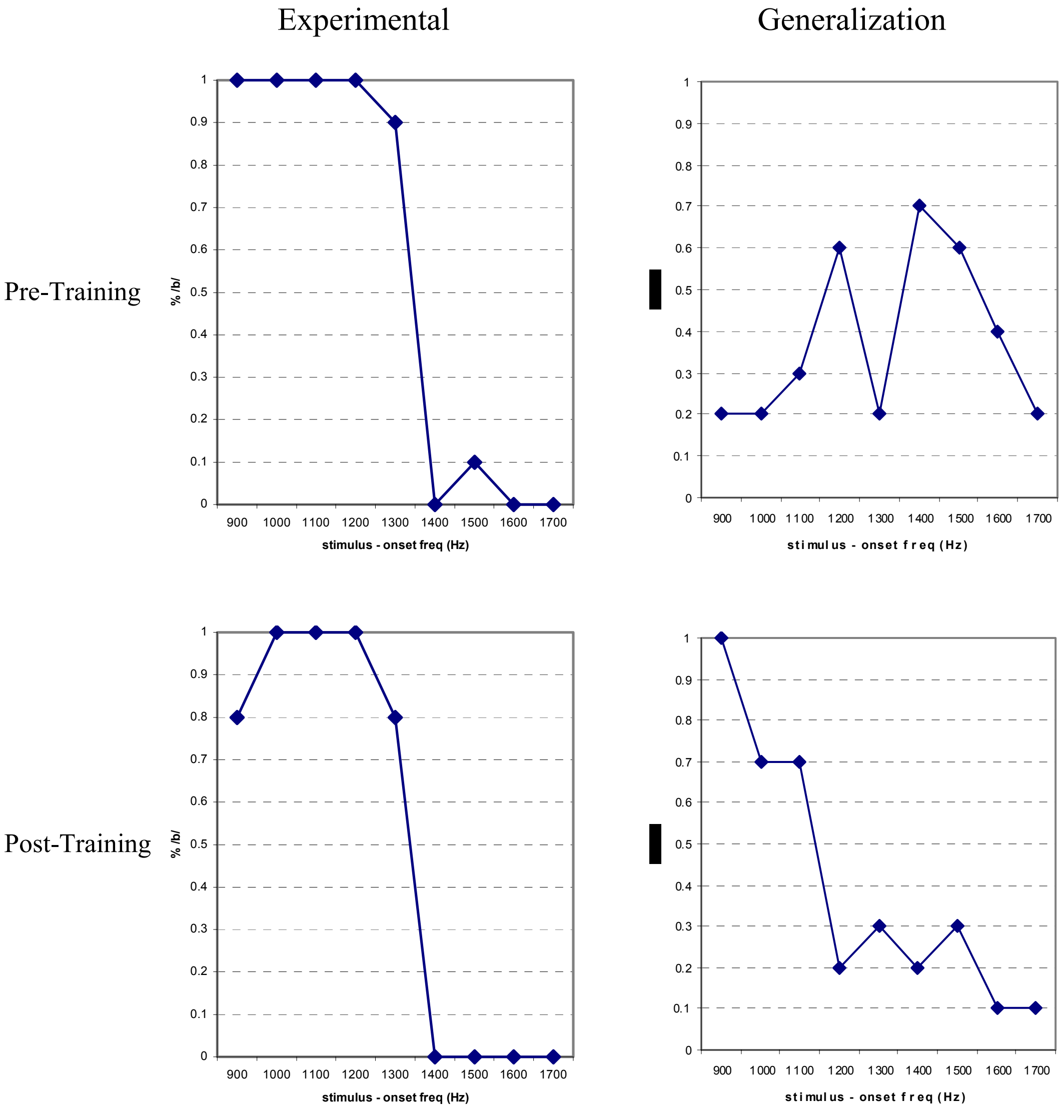

Figure 15. Pre and post training psychometric functions of responses to the experimental and the generalization stimuli for subject 10.

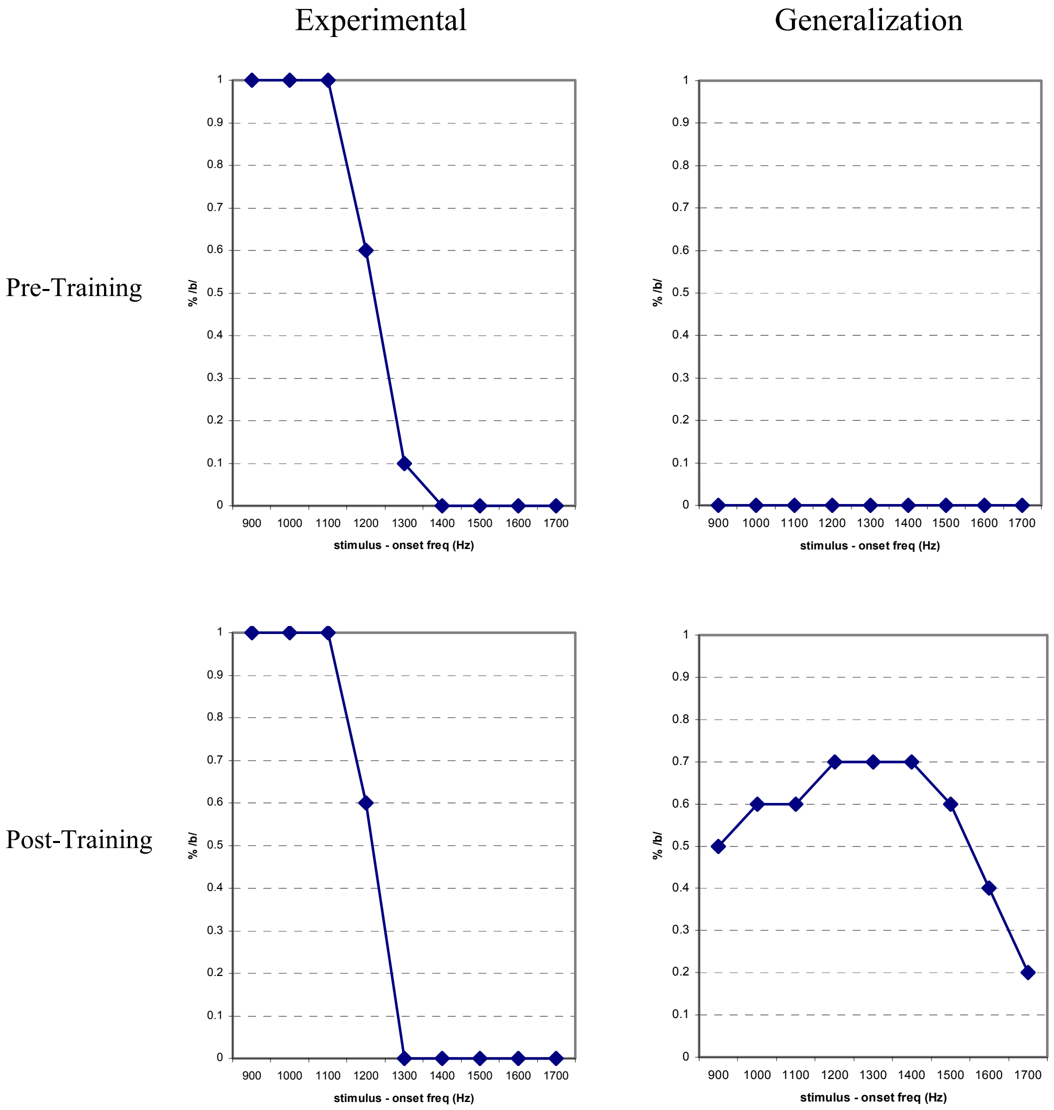

Figure 16. Pre and post training psychometric functions of responses to the experimental and the generalization stimuli for subject 11.

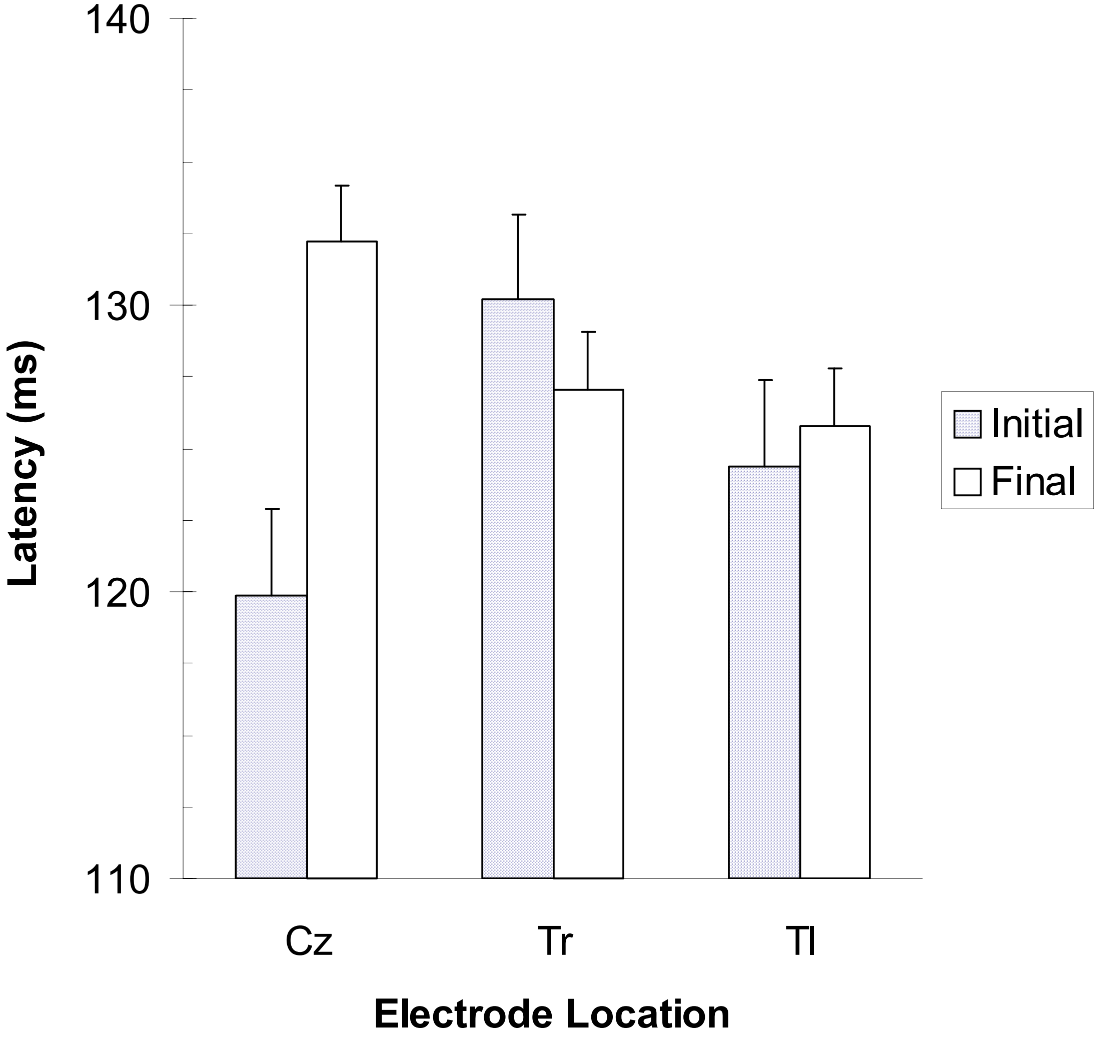

Figure 17. Mean latency of the P100 evoked by the stimulus with an onset frequency of 900Hz by electrode location and time. A significant time by electrode location interaction was found at *p* <0.001. Flags indicate standard errors. N=11 hearing impaired adults.

APPENDIX B

Means and standard deviations are arranged as follows. Measure is P100, N100, P200, N200 absolute latency or P100-N100, N100-P200, P200-N200 peak-to-peak amplitude. Onset, referring to the formant transition onset frequency, is 900 Hz, immediately preceding the categorical boundary (Preceding), immediately following the categorical boundary (Ensuing), and 1700 Hz. Site is electrode location, measured from central vertex (Cz), right temporal lobe (Tr), or left temporal lobe (Tl). Stimulus type (Stim) is experimental (exp) or generalization (gen).

					Pre-training				Post-training			
Measure	Onset	Site	Stim.	N	Min.	Max.	Mean	Std.Dev.	Min.	Max.	Mean	Std.Dev.
P100 latency	900	Cz	Exp	11	97.21	137.42	115.88	13.85	95.81	150.23	123.24	18.04
P100 latency	900	Tr	Exp	11	102.31	156.82	131.54	17.36	101.41	136.92	120.01	12.91
P100 latency	900	Tl	Exp	11	101.61	158.92	123.55	16.54	99.91	148.42	123.48	15.68
P100 latency	900	Cz	Gen	11	102.51	143.45	123.88	14.99	104.71	170.32	141.20	20.19
P100 latency	900	Tr	Gen	11	105.51	164.52	128.84	19.74	109.51	176.42	134.13	16.80
P100 latency	900	Tl	Gen	11	104.21	149.52	125.20	14.14	99.91	198.44	128.11	30.69
N100 latency	900	Cz	Exp	11	120.12	165.22	147.29	13.81	138.72	164.22	151.78	6.84
N100 latency	900	Tr	Exp	11	139.62	170.12	155.52	9.69	121.92	180.62	153.61	15.02
N100 latency	900	Tl	Exp	11	128.32	176.02	150.37	13.37	136.72	170.22	155.59	10.77
N100 latency	900	Cz	Gen	11	108.41	180.92	139.25	22.63	117.42	183.52	144.60	26.25
N100 latency	900	Tr	Gen	11	128.12	193.03	152.91	22.86	122.02	185.02	149.82	21.91
N100 latency	900	Tl	Gen	11	121.22	202.43	148.15	27.38	114.02	191.33	143.42	23.53
P200 latency	900	Cz	Exp	11	180.82	259.33	204.67	23.31	181.02	244.43	205.91	20.19
P200 latency	900	Tr	Exp	11	159.12	255.93	207.56	30.27	183.32	235.53	210.32	17.22
P200 latency	900	Tl	Exp	11	181.92	221.43	196.57	12.01	161.72	249.53	204.36	24.10
P200 latency	900	Cz	Gen	11	164.42	261.23	211.50	31.61	179.12	252.03	218.03	25.13
P200 latency	900	Tr	Gen	11	167.22	240.13	206.32	25.12	176.12	249.63	205.56	25.67
P200 latency	900	Tl	Gen	11	182.32	247.33	210.68	22.19	151.12	246.73	201.22	27.43
N200 latency	900	Cz	Exp	11	213.33	272.04	239.83	17.45	218.23	297.44	256.89	21.95
N200 latency	900	Tr	Exp	11	203.13	298.94	234.53	29.38	202.13	294.64	246.20	26.53
N200 latency	900	Tl	Exp	11	200.33	235.93	220.37	11.05	198.13	272.14	241.54	24.90
N200 latency	900	Cz	Gen	11	217.33	297.54	254.75	22.64	197.23	284.84	248.88	27.70
N200 latency	900	Tr	Gen	11	213.33	299.84	250.59	23.82	197.33	292.14	248.24	33.50
N200 latency	900	Tl	Gen	11	199.73	285.24	245.95	27.60	190.16	280.74	234.95	34.06
P100-N100 amp	900	Cz	Exp	11	0.3760	4.1300	1.5197	1.1292	0.0000	4.4400	1.4486	1.4130
P100-N100 amp	900	Tr	Exp	11	0.1059	3.3800	1.0285	0.9385	0.0000	2.1400	0.5569	0.7114
P100-N100 amp	900	Tl	Exp	11	0.0000	1.6760	0.8303	0.5294	0.1168	2.0300	0.9646	0.5644
P100-N100 amp	900	Cz	Gen	11	0.0000	2.4100	0.5241	0.6944	0.0000	2.3100	0.6484	0.7058
P100-N100 amp	900	Tr	Gen	11	0.0660	1.5800	0.6414	0.4338	0.0000	1.0425	0.3931	0.3150
P100-N100 amp	900	Tl	Gen	11	0.1574	0.8193	0.4870	0.2621	0.0000	0.8730	0.4735	0.2799
N100-P200 amp	900	Cz	Exp	11	2.2300	5.8000	3.4818	1.1368	1.3800	6.9800	3.4369	1.6003
N100-P200 amp	900	Tr	Exp	11	0.6266	4.4400	1.6867	1.1598	0.4054	3.8000	1.7179	1.1076
N100-P200 amp	900	Tl	Exp	11	0.5177	2.1182	1.2952	0.4000	0.4758	2.0700	1.2319	0.4785
N100-P200 amp	900	Cz	Gen	11	1.6121	5.1800	2.9777	1.3055	0.8485	4.8600	2.8594	1.2818
N100-P200 amp	900	Tr	Gen	11	0.4347	3.2800	1.3666	0.8427	0.4656	3.3900	1.4262	0.8774
N100-P200 amp	900	Tl	Gen	11	0.6915	2.1457	1.1623	0.4370	0.5200	1.9400	1.2482	0.4665
P200-N200 amp	900	Cz	Exp	11	0.0000	3.7300	1.3649	1.1373	0.0000	3.5831	1.6606	1.2225
P200-N200 amp	900	Tr	Exp	11	0.0000	1.8396	0.8885	0.6162	0.0000	1.8047	0.9023	0.5121
P200-N200 amp	900	Tl	Exp	11	0.0000	1.7754	0.5978	0.5029	0.0000	1.5574	0.7222	0.4384
P200-N200 amp	900	Cz	Gen	11	0.0000	3.0505	1.3392	0.9458	0.0000	2.8693	1.1792	0.8906
P200-N200 amp	900	Tr	Gen	11	0.0000	1.8145	0.7837	0.4449	0.3844	1.2004	0.8534	0.2650
P200-N200 amp	900	Tl	Gen	11	0.2555	1.6950	0.7830	0.4817	0.0000	1.5048	0.7413	0.3992

					Pre-training				Post-training			
Measure	Onset	Site	Stim.	N	Min.	Max.	Mean	Std.Dev.	Min.	Max.	Mean	Std.Dev.
P100 latency	Preceding	Cz	Exp	11	101.11	146.42	121.47	15.11	101.31	220.95	146.60	32.91
P100 latency	Preceding	Tr	Exp	11	106.91	144.72	123.92	14.30	105.71	151.22	129.31	14.67
P100 latency	Preceding	Tl	Exp	11	107.81	186.42	128.52	22.72	102.11	137.32	120.11	11.50
P100 latency	Preceding	Cz	Gen	11	96.31	163.32	131.10	21.86	99.01	155.62	125.08	17.40
P100 latency	Preceding	Tr	Gen	11	91.71	174.32	129.23	25.14	106.31	177.02	138.46	20.27
P100 latency	Preceding	Tl	Gen	11	102.11	233.55	133.67	36.50	101.01	144.02	121.65	13.41
N100 latency	Preceding	Cz	Exp	11	138.62	164.12	153.54	8.91	138.12	197.13	156.34	15.65
N100 latency	Preceding	Tr	Exp	11	114.42	171.02	149.34	19.18	137.12	172.22	151.68	9.76
N100 latency	Preceding	Tl	Exp	11	121.72	201.13	155.56	20.79	125.02	176.92	153.27	15.61
N100 latency	Preceding	Cz	Gen	11	119.92	226.13	154.48	31.40	120.32	175.02	140.38	16.74
N100 latency	Preceding	Tr	Gen	11	124.52	232.63	159.63	33.47	116.82	206.53	154.69	24.53
N100 latency	Preceding	Tl	Gen	11	128.02	187.73	144.98	17.89	122.62	158.22	139.70	12.28
P200 latency	Preceding	Cz	Exp	11	176.22	269.34	213.77	31.04	179.02	245.73	201.66	20.78
P200 latency	Preceding	Tr	Exp	11	158.82	258.53	205.24	31.73	181.02	260.83	215.97	22.58
P200 latency	Preceding	Tl	Exp	11	159.72	238.43	208.68	23.12	169.92	226.13	200.35	18.68
P200 latency	Preceding	Cz	Gen	11	170.12	292.54	215.58	32.00	148.82	244.43	207.87	27.25
P200 latency	Preceding	Tr	Gen	11	140.62	252.93	206.38	30.96	140.62	240.03	201.48	28.14
P200 latency	Preceding	Tl	Gen	11	172.42	262.94	205.51	28.74	152.32	256.83	195.21	30.96
N200 latency	Preceding	Cz	Exp	11	196.73	289.53	241.43	29.02	198.53	276.04	230.02	23.94
N200 latency	Preceding	Tr	Exp	11	84.06	286.44	217.58	53.08	181.12	275.44	232.52	26.03
N200 latency	Preceding	Tl	Exp	11	188.73	257.43	229.58	19.45	193.13	273.44	231.07	22.71
N200 latency	Preceding	Cz	Gen	11	189.23	307.04	246.03	28.67	214.83	306.74	262.64	27.06
N200 latency	Preceding	Tr	Gen	11	185.92	270.04	240.71	25.75	186.92	288.74	238.05	35.57
N200 latency	Preceding	Tl	Gen	11	208.53	293.74	249.47	24.28	176.82	281.74	244.61	30.67
P100-N100 amp	Preceding	Cz	Exp	11	0.0000	3.5800	1.6470	1.1950	0.0000	4.7600	1.0432	1.3972
P100-N100 amp	Preceding	Tr	Exp	11	0.1286	2.1400	1.0151	0.6896	0.0000	4.5330	1.2110	1.4245
P100-N100 amp	Preceding	Tl	Exp	11	0.0000	2.0532	0.6256	0.6073	0.0000	2.1400	0.8263	0.6619
P100-N100 amp	Preceding	Cz	Gen	11	0.0000	1.3100	0.7129	0.4166	0.0000	1.0200	0.4906	0.2974
P100-N100 amp	Preceding	Tr	Gen	11	0.3690	1.5500	0.8219	0.4259	0.0000	1.0100	0.4151	0.2737
P100-N100 amp	Preceding	Tl	Gen	11	0.0000	0.8185	0.4694	0.2332	0.0000	0.7561	0.3247	0.2289
N100-P200 amp	Preceding	Cz	Exp	11	0.9500	5.3600	3.2871	1.2710	0.9668	6.5200	3.0443	1.5623
N100-P200 amp	Preceding	Tr	Exp	11	0.7848	3.9200	1.8826	0.8969	0.4856	4.2900	1.6201	1.0921
N100-P200 amp	Preceding	Tl	Exp	11	0.5607	1.8250	1.1159	0.4746	0.4313	1.9381	1.2047	0.5636
N100-P200 amp	Preceding	Cz	Gen	11	1.5900	3.5700	2.4182	0.6807	1.0173	3.1100	2.3431	0.8057
N100-P200 amp	Preceding	Tr	Gen	11	0.7582	3.3200	1.3678	0.7879	0.4680	2.7000	1.1659	0.7704
N100-P200 amp	Preceding	Tl	Gen	11	0.5085	1.9120	1.1095	0.3527	0.3744	1.5088	0.9527	0.3841
P200-N200 amp	Preceding	Cz	Exp	11	0.0000	3.5637	1.1456	0.9587	0.0000	1.9300	1.0599	0.6352
P200-N200 amp	Preceding	Tr	Exp	11	0.0000	2.8139	1.2283	0.8193	0.0000	2.0546	0.7385	0.6793
P200-N200 amp	Preceding	Tl	Exp	11	0.0000	1.0396	0.6490	0.3792	0.2716	1.7847	0.8213	0.5377
P200-N200 amp	Preceding	Cz	Gen	11	0.2118	1.6579	0.5928	0.4086	0.5400	2.7921	1.4686	0.6600
P200-N200 amp	Preceding	Tr	Gen	11	0.3012	1.9784	0.9382	0.4779	0.2513	2.4521	0.9266	0.7107
P200-N200 amp	Preceding	Tl	Gen	11	0.0000	1.5850	0.9137	0.4603	0.1504	2.0600	0.8872	0.5140

					Pre-training				Post-training			
Measure	Onset	Site	Stim.	N	Min.	Max.	Mean	Std.Dev.	Min.	Max.	Mean	Std.Dev.
P100 latency	Ensuing	Cz	Exp	11	100.81	139.82	120.75	14.22	100.31	189.03	134.44	23.48
P100 latency	Ensuing	Tr	Exp	11	91.81	365.94	140.75	75.54	99.51	138.42	121.42	11.32
P100 latency	Ensuing	Tl	Exp	11	103.31	137.72	119.52	11.69	103.61	158.92	127.57	20.16
P100 latency	Ensuing	Cz	Gen	11	81.11	156.32	121.06	21.21	102.41	145.52	125.40	16.07
P100 latency	Ensuing	Tr	Gen	11	101.81	189.73	124.95	28.74	105.81	167.85	129.47	19.79
P100 latency	Ensuing	Tl	Gen	11	107.21	153.02	122.23	14.02	106.41	140.32	122.38	11.72
N100 latency	Ensuing	Cz	Exp	11	135.52	169.62	151.23	9.86	122.02	206.33	152.20	21.21
N100 latency	Ensuing	Tr	Exp	11	137.52	173.12	156.82	12.10	120.62	182.22	149.75	17.20
N100 latency	Ensuing	Tl	Exp	11	132.62	167.42	146.09	12.38	120.92	180.22	152.74	15.58
N100 latency	Ensuing	Cz	Gen	11	109.51	181.92	136.86	24.48	120.32	603.58	184.07	140.50
N100 latency	Ensuing	Tr	Gen	11	117.42	218.23	152.85	36.72	118.72	650.41	198.56	152.60
N100 latency	Ensuing	Tl	Gen	11	124.02	176.32	140.85	16.44	120.72	181.53	139.38	18.76
P200 latency	Ensuing	Cz	Exp	11	175.62	259.73	206.56	23.03	181.32	266.64	203.77	23.64
P200 latency	Ensuing	Tr	Exp	11	187.12	263.14	209.33	22.20	150.12	256.13	199.63	29.91
P200 latency	Ensuing	Tl	Exp	11	156.82	234.73	196.62	20.69	180.22	219.43	199.31	11.09
P200 latency	Ensuing	Cz	Gen	11	189.93	250.33	216.18	18.85	114.41	257.93	202.73	38.17
P200 latency	Ensuing	Tr	Gen	11	182.32	255.93	216.19	28.20	158.42	359.52	226.25	55.58
P200 latency	Ensuing	Tl	Gen	11	166.72	217.53	193.45	15.85	164.52	262.23	209.49	28.48
N200 latency	Ensuing	Cz	Exp	11	210.43	299.44	244.23	26.10	215.73	287.24	240.04	20.39
N200 latency	Ensuing	Tr	Exp	11	210.53	289.04	241.41	23.85	82.57	293.94	223.17	57.19
N200 latency	Ensuing	Tl	Exp	11	171.62	278.14	228.31	31.60	213.03	284.54	234.09	19.96
N200 latency	Ensuing	Cz	Gen	11	150.31	288.34	244.77	37.92	135.26	283.84	240.13	39.51
N200 latency	Ensuing	Tr	Gen	11	208.53	277.54	243.32	25.78	180.42	284.04	245.82	25.61
N200 latency	Ensuing	Tl	Gen	11	182.42	255.53	232.57	21.76	192.73	291.54	247.80	28.26
P100-N100 amp	Ensuing	Cz	Exp	11	0.1700	3.9900	1.5248	1.2261	0.0000	3.6200	0.9096	1.1023
P100-N100 amp	Ensuing	Tr	Exp	11	0.0000	3.0300	1.1446	0.9680	0.0000	2.5900	0.7027	0.7335
P100-N100 amp	Ensuing	Tl	Exp	11	0.2677	2.2500	0.9477	0.6521	0.1651	1.5235	0.6474	0.4245
P100-N100 amp	Ensuing	Cz	Gen	11	0.0000	2.3800	0.5921	0.6853	0.0000	1.4200	0.5040	0.5209
P100-N100 amp	Ensuing	Tr	Gen	11	0.3022	1.9400	1.0164	0.4916	0.0000	1.8758	0.5616	0.5344
P100-N100 amp	Ensuing	Tl	Gen	11	0.1346	0.9050	0.4987	0.2516	0.0000	1.4795	0.3986	0.4424
N100-P200 amp	Ensuing	Cz	Exp	11	1.8064	5.4700	3.4638	1.1922	0.8839	5.2900	3.1970	1.3231
N100-P200 amp	Ensuing	Tr	Exp	11	0.8461	3.7800	1.7849	0.9630	0.5538	3.3700	1.6951	0.9060
N100-P200 amp	Ensuing	Tl	Exp	11	0.5408	2.7600	1.4657	0.5723	0.2927	2.1167	1.0204	0.5409
N100-P200 amp	Ensuing	Cz	Gen	11	1.2954	4.6300	2.7325	0.8442	1.2958	5.2850	2.8850	1.2762
N100-P200 amp	Ensuing	Tr	Gen	11	0.4912	4.1200	1.5590	0.9870	0.0000	2.5633	1.1634	0.6972
N100-P200 amp	Ensuing	Tl	Gen	11	0.5490	1.7152	1.2182	0.3857	0.0000	1.7639	0.7858	0.4865
P200-N200 amp	Ensuing	Cz	Exp	11	0.0000	3.6396	1.3393	0.9650	0.6900	3.6239	1.6288	0.8345
P200-N200 amp	Ensuing	Tr	Exp	11	0.0000	1.8900	1.0057	0.6097	0.0000	1.6700	0.9446	0.5518
P200-N200 amp	Ensuing	Tl	Exp	11	0.3013	1.5102	0.8190	0.3355	0.3421	1.0917	0.7452	0.2600
P200-N200 amp	Ensuing	Cz	Gen	11	0.0000	3.4592	1.3655	0.9796	0.0000	1.9347	0.8472	0.6518
P200-N200 amp	Ensuing	Tr	Gen	11	0.4460	2.2914	0.8951	0.5193	0.0000	1.1100	0.5984	0.3807
P200-N200 amp	Ensuing	Tl	Gen	11	0.5153	1.7594	0.9904	0.3862	0.0000	1.1476	0.6404	0.3170

					Pre-training				Post-training			
Measure	Onset	Site	Stim.	N	Min.	Max.	Mean	Std.Dev.	Min.	Max.	Mean	Std.Dev.
P100 latency	1700	Cz	Exp	11	77.55	136.52	110.18	16.83	101.71	144.42	117.27	15.26
P100 latency	1700	Tr	Exp	11	95.21	141.52	120.62	15.56	98.01	134.12	115.13	11.47
P100 latency	1700	Tl	Exp	11	101.01	142.72	123.49	15.47	97.51	147.22	126.67	15.77
P100 latency	1700	Cz	Gen	11	102.91	169.52	129.36	23.11	100.51	143.82	120.01	14.20
P100 latency	1700	Tr	Gen	11	102.01	132.92	120.75	8.22	103.71	168.62	128.92	19.81
P100 latency	1700	Tl	Gen	11	102.01	157.22	122.17	16.56	106.01	200.53	132.32	29.16
N100 latency	1700	Cz	Exp	11	116.92	163.12	142.24	15.18	118.92	157.12	140.21	13.96
N100 latency	1700	Tr	Exp	11	117.72	167.42	148.20	15.35	117.62	185.82	144.87	20.61
N100 latency	1700	Tl	Exp	11	140.62	175.72	151.96	9.33	135.02	192.53	154.29	17.41
N100 latency	1700	Cz	Gen	11	118.42	197.73	144.87	27.41	114.52	147.72	131.85	10.58
N100 latency	1700	Tr	Gen	11	102.61	149.12	130.16	15.91	96.41	189.73	146.67	27.47
N100 latency	1700	Tl	Gen	11	127.42	196.73	144.53	20.02	123.22	221.33	153.80	33.20
P200 latency	1700	Cz	Exp	11	181.82	256.33	208.66	23.64	175.62	255.03	199.95	23.92
P200 latency	1700	Tr	Exp	11	178.02	240.83	206.45	20.70	164.62	256.13	204.93	27.79
P200 latency	1700	Tl	Exp	11	181.52	237.23	199.14	18.89	186.62	255.33	211.96	23.51
P200 latency	1700	Cz	Gen	11	165.82	254.13	208.07	27.94	169.92	264.74	205.72	31.13
P200 latency	1700	Tr	Gen	11	139.12	238.73	181.75	31.95	148.22	232.53	191.36	28.87
P200 latency	1700	Tl	Gen	11	174.42	236.83	195.48	20.30	180.82	279.34	213.48	31.52
N200 latency	1700	Cz	Exp	11	197.73	287.04	244.17	28.03	200.53	247.53	224.66	14.58
N200 latency	1700	Tr	Exp	11	202.23	278.44	236.93	22.19	203.83	288.64	236.68	25.59
N200 latency	1700	Tl	Exp	11	199.63	260.43	228.55	21.60	216.03	256.53	237.12	14.17
N200 latency	1700	Cz	Gen	11	213.73	287.94	247.35	21.51	219.23	288.94	253.57	21.48
N200 latency	1700	Tr	Gen	11	156.62	267.54	214.11	32.09	169.12	259.83	217.52	27.44
N200 latency	1700	Tl	Gen	11	192.43	282.54	231.40	27.96	218.73	289.64	252.16	25.07
P100-N100 amp	1700	Cz	Exp	11	0.1242	3.8000	1.5074	1.1541	0.1500	2.4900	0.8553	0.8119
P100-N100 amp	1700	Tr	Exp	11	0.2224	2.2200	1.0775	0.7156	0.0000	2.2600	0.5965	0.7523
P100-N100 amp	1700	Tl	Exp	11	0.1536	1.8400	0.8945	0.5196	0.2646	2.0700	0.7482	0.5585
P100-N100 amp	1700	Cz	Gen	11	0.0000	1.0939	0.6282	0.3764	0.0000	0.7300	0.3371	0.2643
P100-N100 amp	1700	Tr	Gen	11	0.0000	1.4000	0.3790	0.4120	0.0000	1.4421	0.5123	0.4663
P100-N100 amp	1700	Tl	Gen	11	0.3212	1.2257	0.6293	0.2742	0.1243	1.3700	0.6460	0.4028
N100-P200 amp	1700	Cz	Exp	11	2.1800	5.1100	3.5936	1.1088	0.8931	5.7000	3.1127	1.3634
N100-P200 amp	1700	Tr	Exp	11	0.6839	4.2700	1.9487	1.1185	0.6810	3.5900	1.6771	1.0069
N100-P200 amp	1700	Tl	Exp	11	0.7617	2.0500	1.4369	0.4469	0.1214	1.9244	1.0743	0.6847
N100-P200 amp	1700	Cz	Gen	11	0.6713	4.2100	2.5341	1.0417	1.7103	4.7500	2.7264	0.8939
N100-P200 amp	1700	Tr	Gen	11	0.7297	3.3100	1.5621	0.7610	0.4808	3.1200	1.4199	0.9278
N100-P200 amp	1700	Tl	Gen	11	0.2853	1.9400	1.1081	0.4341	0.3049	1.6932	1.1145	0.4433
P200-N200 amp	1700	Cz	Exp	11	0.0000	3.1000	1.4873	0.8692	0.0000	2.3304	1.0282	0.7175
P200-N200 amp	1700	Tr	Exp	11	0.3301	1.7587	0.9209	0.3788	0.0000	1.4495	0.8126	0.4641
P200-N200 amp	1700	Tl	Exp	11	0.6144	1.1437	0.8297	0.1738	0.0000	1.1860	0.5312	0.3516
P200-N200 amp	1700	Cz	Gen	11	0.3905	2.5261	1.3436	0.7369	0.0000	3.5831	1.4804	1.0745
200-N200 amp	1700	Tr	Gen	11	0.0000	1.4155	0.7788	0.4448	0.0000	1.1294	0.6086	0.3206

Vita

Clifford Anthony Franklin Jr. was born in Montgomery, Alabama on June 19, 1967. One of five children, Cliff was raised in a nurturing environment. He graduated from Sidney Lanier High School in Montgomery in 1985. From there he attended the University of Alabama and Auburn University at Montgomery. He graduated from Auburn University at Montgomery with a B.S. degree in Education for Secondary Mathematics. He taught mathematics and computer programming at Carver High School in Montgomery before entering Auburn University's graduate program for communication disorders. After graduating from Auburn University with a Master of Communication Disorders (M.C.D.) degree, Cliff worked as a clinical audiologist at Norwood Clinic in Birmingham, Alabama. He entered the University of Tennessee to work on his Ph.D. in 1999.

In conjunction to his professional endeavors, Cliff has been a member of the Alabama Air National guard since 1988. After working as a crew chief on the F-16 fighter aircraft, Cliff earned his commission in 2001. He is currently the commander of the 187th Services Flight in Montgomery.

Cliff is currently employed as an assistant professor at the University of Arkansas for Medical Sciences and the University of Arkansas at Little Rock He presently lives in Little Rock, Arkansas with his wife Jennifer.