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THE USE OF SIMULATION TECHNIQUES TO INVESTIGATE THE EFFECTS OF CONDUCTIVE HEARING LOSS ON THE AUDITORY BRAINSTEM RESPONSE

by

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THESIS APPROVAL PAGE

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ABSTRACT

The Use of Simulation Techniques to Investigate the Effects of Conductive Hearing Loss on the Auditory Brainstem Response

Molly Bishop

A click-evoked Auditory Brainstem Response (ABR) was recorded on 28 normal hearing adult participants to determine the effects of different degrees of conductive hearing loss on the response properties of the ABR. Participants were divided at random into two groups: the normal hearing group and the simulated conductive hearing loss group.

In the normal hearing group, baseline behavioral pure tone audiometry from 250-8000 Hz and acoustic immittance testing (tympanometry and contralateral acoustic reflex thresholds from 500-2000 Hz) were performed to ensure normal hearing and middle ear function. Then, ABR testing was performed in both right and left ears to click stimuli beginning at 80 dBnHL. Stimulus intensity was decreased in 10 dB increments until a stimulus intensity of 30 dBnHL was reached. At stimulus intensities less than 30 dB nHL, stimulus intensity was decreased in 5 dB increments until the participant's ABR threshold was determined. In the simulated conductive hearing loss group, baseline behavioral pure tone audiometry from 250-8000 Hz and acoustic immittance testing (tympanometry and contralateral acoustic reflex thresholds from 500-2000 Hz) were performed to ensure normal hearing and middle ear function. Then, 5 mm of moleskin was placed in the

tubing for the ER3A insert receivers and pure tone air conduction thresholds were re-measured in each ear. For the conductive group, the ABR was recorded using the ER3A insert receivers with moleskin. The ABR was recorded in both right and left ears to click stimuli beginning at 80 dBnHL. Stimulus intensity was decreased in 10 dB increments until a stimulus intensity of 60 dBnHL was reached. At stimulus intensities less than 60 dBnHL, stimulus intensity was decreased in 5 dB increments until the participant's ABR threshold was determined.

For both groups, results revealed an increase in the mean absolute latencies of waves I, III, and V as stimulus intensity decreased. In contrast, results showed a decrease in the mean peak-to-peak amplitudes for waves I-I' and V-V' as a function of stimulus intensity. Mean interpeak latency values were consistent across stimulus intensities. Mean absolute latency values for all waves were greater for the simulated hearing loss group than the normal hearing group. In contrast, the mean peak-to-peak amplitude values for waves I-I' and V-V' were smaller for the simulated hearing loss group than the normal hearing group. These results were compared to previous data collected in the ABR literature on both normal hearing and conductive hearing loss participants. Results for both groups in the current study were in good agreement with the ABR literature as seen in the mean ABR values and the variability represented by standard deviation measurements.

The data collected from this study will be used to develop a parametric approach to generating simulated responses for the commercially available Auditory Brainstem Response (ABR) recording simulator, ISAO by Intelligent Hearing Systems. This data will serve as basis for developing functions of response characteristics such as peak latency and amplitude as well as recording parameters like intensity, rate and stimulus characteristics. Further research should be conducted to determine the effects of other stimulus parameters on the ABR. These stimulus parameters include rate, polarity, and frequency.

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Chapter 1

Introduction

Auditory evoked potentials (AEPs) are electrical responses from the peripheral and/or central nervous systems that are generated by externally presented auditory stimuli (Hood, 1998). These potentials are classified based on their latency, relationship to the stimulus, and underlying neural generators. Specifically, the present study is investigating the Auditory Brainstem Response (ABR). The ABR is an electrophysiologic measure arising from the auditory nerve and brainstem structures (Burkard & Don, 2015). The ABR has two primary clinical applications. These areas include: identification of neurological pathologies in the eighth nerve and auditory pathways of the brainstem and estimation of hearing sensitivity (Hood, 1998).

In the current study, we are studying the effect of conductive hearing loss on the ABR. In this study, click-evoked ABRs were recorded in two groups; the normal hearing group and the simulated conductive hearing loss group. The purpose of this study is to obtain click-evoked ABR data in order to create new AEP Libraries in the Intelligent Hearing System (IHS) Baby Isao Simulator as well as to provide actual ABR data which can be used to model the effects of different degrees of conductive hearing loss on the response properties of the ABR. The ABR data was collected on young normal hearing adults. In the hearing loss group, moleskin was inserted into the receiver tubing to simulate a conductive hearing impairment. Adults with normal hearing and simulated conductive hearing loss participated in this study to accurately reflect both a normal functioning auditory system and an auditory system with conductive hearing impairment.

At all stimulus intensities, the ABR recordings from each participant were analyzed for various latency and amplitude measurements. Latency measurements included the absolute latency measurements of waves I, III, and V, the interpeak latencies of waves I-III, III-V, and I-V, and the interaural latency differences of IT5 and I-V. The amplitude measurements included the peak-to-peak amplitude values of waves I-I' and V-V' and the V/I amplitude ratio. The results from the normal hearing group were compared to simulated conductive hearing loss group to determine if there were any differences in these latency and amplitude values. As expected, the simulated conductive hearing loss group had greater absolute latency values for all waves and smaller peak-to-peak amplitude values for waves I-I' and V-V' compared to the normal hearing group.

The results from the current study were compared to previous studies in the ABR literature on adults with normal hearing and conductive hearing loss. Descriptive statistics including means and standard deviation were calculated on all latency and amplitude measurements. In general, the mean latency and amplitude results for both groups were in good agreements with the data from previous ABR studies.

The data collected from this study will be used to develop a parametric approach to generating simulated responses for the commercially available Auditory Brainstem Response (ABR) recording simulator, ISAO by Intelligent Hearing Systems. This data will serve as basis for developing functions of response characteristics such as peak latency and amplitude as well as recording parameters like intensity, rate and stimulus characteristics. These functions will then be used to synthesize responses on the fly based on the detected stimulus characteristics and various noise recording conditions. This approach will provide a more generalized simulation technique that will not require a discrete library of sample recordings.

Following the current study, further research should be conducted to determine the effects of other stimulus parameters on the ABR. These stimulus parameters include rate, polarity, and frequency. Ultimately, the data from these projects can be used to develop additional functions of response characteristics for simulation.

Chapter 2

Literature Review

Auditory Evoked Potentials

Auditory evoked potentials (AEPs) are electrical brain responses in the peripheral and/or central nervous systems that are generated by externally presented auditory stimuli (Hood, 1998). Auditory evoked potentials are comprised of a series of positive peaks and negative troughs elicited by acoustic stimuli. These electrical responses can be recorded from surface electrodes placed on the scalp according to the International 10-20 system (Jasper, 1958). Activity from AEPs are generated by a variety of sites within the peripheral and/or central auditory nervous systems including the cochlea, auditory nerve, auditory brainstem, thalamus, and auditory cortex (Burkard & Don, 2015). There are several types of AEPs that can vary in terms of latency, neural generators, stimulus, response dependencies, and clinical applications (Burkard & Don, 2015). Some of these AEPs include the Auditory Brainstem Response (ABR), Electrococleography (EcochG), the Middle Latency Response (MLR), and the Late Auditory Evoked Potentials (LAEP). In order to further understand these potentials, Picton (1990) proposed four different classification schemes. These classification schemes will be briefly discussed in the next section.

Hallowell Davis (1976) proposed the first AEP classification scheme based primarily on latency. Latency is the time (in milliseconds) between the onset of the stimulus and the onset of the response (Picton, 2010). Davis (1976) classified AEPs into five categories: first, fast, middle, slow, and late. The “first” responses occur between 0-5 milliseconds (ms) post-stimulus onset. “First” auditory evoked potentials include the

Eighth Nerve Compound Action Potential (CAP) and waves I and II of the Auditory Brainstem Response. The "fast" AEPs occur between 2-20 ms and include waves III, IV, and V of the ABR. The "first" and "fast" latency classifications are commonly grouped together as "early responses" (Picton, 1990). The Middle Latency Response (MLR) follows the "first" and "fast" latency responses and occurs between 10-100 ms. The MLR is composed of waves Na, Pa, and Nb. The "slow" and "late" responses are often categorized together as the Late AEPs. These responses occur at 50-300 ms and 150-1000 ms, respectively. The slow response is composed of the slow "vertex" potential and includes waves P1, N1, P2, and N2. The late response contains the Mismatch Negativity (MMN) and waves N2b, P3b, and N4.

The second classification scheme suggested by Picton (1990) was the relationship of the response to the stimulus. Picton defined three types of responses: transient, sustained, and steady-state (2010). Transient evoked potentials occur following a change in a single stimulus (Picton, 2010). Neural locations generating these responses are onset-sensitive which means they respond to the onset of the stimulus (Hood, 1998). Examples of transient evoked potentials include the VIIIth nerve CAP, ABR, MLR, and Slow Cortical Response. Sustained evoked potentials are responses that reflect continual stimulation (Hood, 1998). The Frequency Following Response (FFR) is an example of a "sustained" response. The third type of response is the steady state response. The steady state response is evoked by rapidly repeating stimuli. This response is elicited when the stimulus rate is sufficiently fast and causes the response to the first stimulus to overlap with the response to the next stimulus (Hall, 2007). The Auditory Steady State Response (ASSR) is an example of a steady state response.

The third major classification scheme of AEPs describes their underlying neural generators. Numerous studies, in animals and humans, have focused on determining the various locations from which these responses are generated. Early AEPs have been determined to originate from eighth nerve auditory pathways and the brainstem (Don & Kwong, 2009). The MLR is primarily generated by the auditory cortex with some sub-cortical contributions as well (McGee & Kraus, 1996). Lastly, the late AEPs originate from the auditory cortex with input from areas near the Sylvian Fissure as well.

The fourth classification scheme categorizes AEPs as either Sensory Evoked Potentials or as Processing-Contingent Potentials (PCPs). Sensory evoked potentials, or exogenous potentials, are obligatory responses. The characteristics of these potentials are determined by external stimuli such as a click or a toneburst (Hood, 1998). The eighth nerve CAP, ABR, MLR, and Slow Cortical Responses are all examples of sensory evoked potentials. In contrast, PCPs, or endogenous potentials, are influenced by internal cognitive processes (Hood, 1998). These potentials require additional brain processing of the stimulus. An example of a Processing-Contingent Potential is the P300. The P300 requires the subject to not only detect the auditory stimulus, but also to discriminate between the different acoustic stimuli (Picton, 2010).

Since the ABR is the main focus of this study, the remainder of this literature review will discuss this response in more depth. Based on the classification schemes discussed earlier, the ABR is a fast transient response. The ABR represents neural activity from the eighth cranial (vestibulocochlear) nerve and tracts within the brainstem (Hood, 1998). Additionally, it is a sensory evoked potential that is responsive and dependent on auditory stimulation. Given that the ABR is a widely used evoked potential in clinical settings, it is important to understand the history of the response.

History of the Auditory Brainstem Response

The Auditory Brainstem Response includes a series of 5 to 7 positive peaks arising from the auditory nerve and brainstem structures (Burkard & Don, 2015). The ABR is recorded to a brief auditory signal from electrodes placed on the scalp (Hood, 1998). This series of waveforms occur within approximately 2 to 12 ms after the onset of stimulus (Hood, 1998). The ABR is typically recorded to brief transient stimuli, such as a click or a toneburst stimulus. In 1971, Don Jewett and John Williston were among the first researchers to study the ABR and define each of its peaks.

In 1970, Jewett conducted a study in which he examined evoked potentials recorded to high intensity click stimuli in eighteen cats. Recordings were made differentially between surface electrodes on various locations along the cats' bodies and needle electrodes along the auditory pathway. In the recordings, Jewett observed a display of four positive peaks that he labeled peaks P1-P4. He found that the four positive waves recorded from the surface electrodes occurred simultaneously with the peaks recorded along the auditory pathway (Jewett, 1970).

In 1971, Jewett and Williston completed a similar study on twelve normal hearing adults to further understand the electric potentials in humans. Surface electrodes were placed on the participants' scalp and their right ear lobes. The ABR was recorded with click stimuli presented at 60-75 dB above the subject's threshold. Jewett and Williston observed a distinct series of waves in the first 9 ms following stimulus onset as seen in Figure 1 below. These researchers chose to label those waves sequentially with Roman numerals I through VII (Jewett & Williston, 1971). These researchers found similarities in the ABR waveforms recorded in all twelve subjects. In every subject, the first six peaks were detectable and the latency of each peak was essentially the same. Additionally, the morphology of the ABR waveform was similar in all participants. This study was the first to describe the unique characteristics of the ABR waveform in humans. Those distinct characteristics will be discussed in greater detail below.

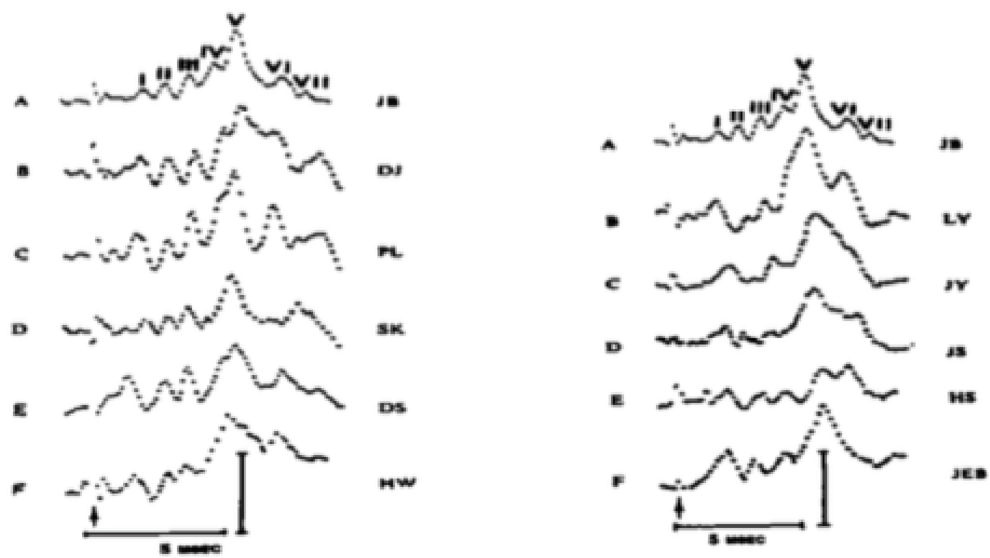

Figure 1. Far-field recordings from twelve normal hearing subjects to high-intensity click stimuli. Waves are labeled with Roman numbers I through VII (Jewett & Williston, 1971).

Clinical Applications of the ABR

The ABR has primary clinical applications in two different areas. These areas include: identification of neurological pathologies in the eighth nerve and auditory pathways of the brainstem as well as estimation of hearing sensitivity (Hood, 1998). The main diagnostic application of the otoneurologic ABR is detecting retrocochlear pathologies, like VIIIth nerve tumors. Two major measurements, peak latencies and peak-to-peak amplitudes, are used to evaluate the otoneurologic ABR. These measures will be discussed in greater detail in the next section of this literature review.

The second primary application of the ABR, audiologic threshold estimation, is often used in patients that cannot provide reliable hearing thresholds using traditional behavioral methods (Hood, 1998). These patients include both pediatric and difficult-to-test populations. In these individuals, clinicians may not be able to obtain accurate behavioral thresholds and alternative methods must be used to estimate these thresholds (Burkard & McNerney, 2009). Audiologic threshold estimation is also desirable when one wants to know the sensitivity of each ear separately to estimate auditory function at different frequencies (Hood, 2015). Threshold estimation ABRs are recorded to frequency-specific stimuli and focus primarily on the identification of wave V. In order to predict a threshold, the stimulus intensity is lowered until a replicable wave V can no longer be detected (Gelfand, 2009). This recording approach has been shown to predict thresholds within 10 dB of behavioral pure tone thresholds (Hood, 1998).

Description of the Response Characteristics

Several ABR characteristics can be examined to determine the integrity of the eighth nerve and auditory brainstem pathways. These parameters fall into three categories: latency measurements, amplitude measurements, and overall morphology of the response. An ABR recorded to a high intensity click stimulus in a normal hearing adult is shown in figure 2 below.

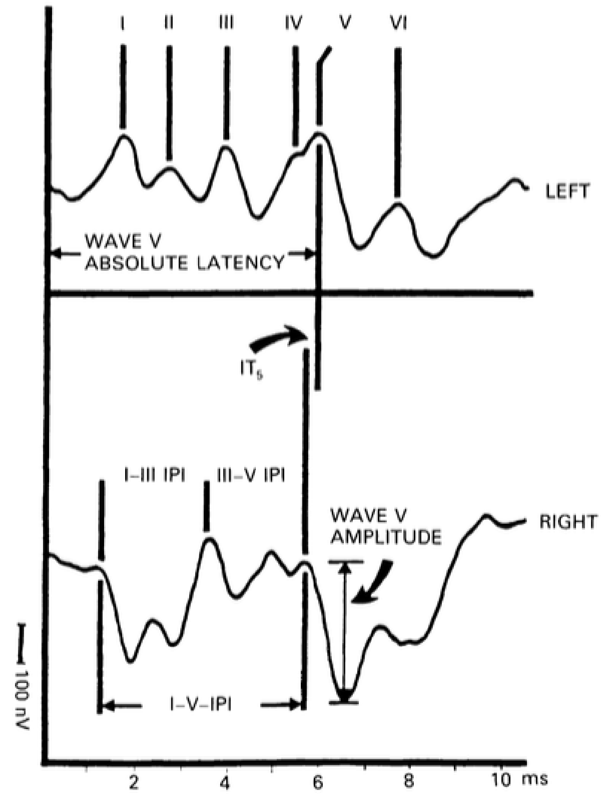

Figure 2. An ABR recorded to a high-intensity click stimulus in a normal hearing adult. Waves I through VI are labeled. Also pictured are the absolute latency of wave V, the peak-to-peak amplitude of wave V, the interpeak latencies (IPI) of I-III, III-V, and I-V, and the interaural latency difference of wave V (IT5) (Abramovich, 2013)

As described above, several latency measurements are analyzed to determine whether or not an ABR waveform is normal. These measurements include absolute peak latency, interpeak latency (IPL), and interaural latency differences. Absolute latency is the time interval between the onset of the stimulus and the peak of the waveform, in milliseconds (ms) (Hood, 1998). Absolute latencies are primarily measured for waves I, III, and V. Latency of the ABR is the most reliable measurement and provides the basis for ABR interpretation (Hood, 1998). The second type of latency measure for the ABR is interpeak latency. Interpeak latency is the time interval between the different peaks of the

ABR (Hood, 1998). Interpeak latencies for waves I to III, waves III to V, and waves I to V are used in the clinical interpretation of the otoneurologic ABR (Hood, 1998). The third latency measurement used to assess the otoneurologic ABR is the interaural latency difference of wave V, or IT5. The interaural latency difference compares the absolute latencies of wave V measured from the right and left ears at equal stimulus intensities (Hood, 1998). If peripheral hearing sensitivity is similar in both ears, the latency of wave V should differ minimally between the ears (≤ 0.2 ms) (Burkard & Don, 2015).

Amplitude measurements are used in conjunction with latency measurements to assess otoneurologic ABRs. The primary amplitude measurements are peak-to-peak amplitudes of wave I and wave V. Peak-to-peak amplitudes are measured from the positive peak of the wave (wave I or wave V) to the following negative trough (wave I' or wave V') and are reported in microvolts (μV) (Hood, 1998). The second amplitude value that is measured clinically is the wave V to wave I amplitude ratio. The wave V/I amplitude ratio is calculated by dividing the peak-to-peak amplitude of wave V by the peak-to-peak amplitude of wave I (Hood, 1998). A wave V/I amplitude ratio greater than or equal to 0.5 μV indicates a normal functioning system. If a wave V is significantly smaller than wave I (amplitude ratio <0.5 μV), it can be suggestive of a retrocochlear pathology (Musiek, Gonzalez, & Baran, 2015). It is important to note that amplitude values are more variable than latency measurements and therefore should be interpreted with caution (Hood, 1998).

The final characteristic that clinicians use to assess the integrity of the ABR is the morphology of the response. A normal ABR recording that is obtained at a high stimulus intensity should consist of characteristic peaks and troughs. Generally, an ABR recorded in a normal hearing individual will contain well-defined waves I through V (Hood, 1998). However, the morphology of the ABR recording may appear in various configurations across individuals and still be considered normal (Hall, 2007). One component of the ABR that is sometimes difficult distinguish is the shape of the wave IV-V complex. The wave IV-V complex can combine into a single peak, wave IV may have a greater amplitude than wave V, or the wave V may have a higher amplitude than wave IV. Due to the variability in ABR morphology, it is important to maintain consistency in waveform identification and obtain multiple recordings of waveforms (Hood, 1998).

Neural Generators of the ABR

In order to study the underlying neural generators of the ABR, researchers have primarily used two techniques. In the first technique, researchers compared recordings from surface recording potentials to recordings obtained from structures exposed during neurosurgery procedures (Moller & Janetta, 1981, 1982). The second technique involved comparing ABRs from patients with known pathologies to normal controls. Studies to determine the neural generators of the ABR have been conducted on both animal and human participants. In the following section of the literature review, the evidence from both animal and human studies will be discussed.

In 1975, Buchwald and Huang were among the first researchers to study the generators of the ABR. In a series of lesion experiments, investigators recorded short-latency evoked potentials from the vertex of ten adult cats. In order to determine the origins of each component, these researchers made specific lesions in the cats at the levels of the cochlear nucleus, inferior colliculus, and auditory nerve. Buchwald and Huang (1975) found that peak I was a reflection of the auditory nerve discharge and peak

II originated from the cochlear nucleus. Peak III was generated primarily by the crossed pathways of the superior olivary complex. Peak IV originated from the ventral nucleus of the lateral lemniscus and the preolivary complex. Finally, peak V required input from the crossed projections of the inferior colliculus (Buchwald & Huang, 1975).

Following the success that Buchwald and Huang had in determining the neural generators of ABRs in cats, researchers were interested in studying these specific neural generators in human participants. Throughout the 1980s, Moller and colleagues conducted multiple studies to investigate the neural generators of the human ABR (Moller & Janetta, 1981; Moller & Janetta, 1982a; Moller & Janetta, 1982b). In these studies, participants were undergoing surgical operations for cranial nerve dysfunction. ABR recordings were taken before and after the operation. The researchers placed surface electrodes on the scalp and mastoids. A 2000 Hz toneburst stimulus was used to record the ABR. During the operations, needle electrodes were placed directly on the eighth nerve, cochlear nucleus, superior olivary complex, lateral lemniscus, and inferior colliculus. Investigators compared the latencies of responses from the surface electrodes to the latencies of the recordings from the needle electrodes.

From these comparisons, Moller and Janetta concluded that wave I of the ABR is generated from the distal portion of the eighth nerve. They found that waves III and V both originate from nuclei within the auditory brainstem. Researchers determined that wave III came from the cochlear nucleus and the superior olivary complex (Moller & Janetta, 1981, 1982a). Finally, Moller and Janetta determined that wave V of the ABR is generated by the lateral lemniscus and inferior colliculus (1982a & 1982b).

Using a similar method, Hashimoto, Ishiyama, Yoshimoto, and Nemoto studied the ABRs recorded from surface electrodes overlying the eighth nerve, brainstem, thalamus, cerebellar cortex and cerebral cortex (1981). The researchers found a P3 component at the level of the pons that correlated well with the wave III component found in scalp recordings. They also reported that the P5 component with similar latency and amplitude to wave V of the ABR originated from the inferior colliculus (Hashimoto, Ishiyama, Yoshimoto, & Nemoto, 1981). Hashimoto and colleagues' findings support the results reported by Moller and Janetta on the neural generators of ABR waves III and V.

The evidence from these animal and human ABR studies suggest that the neural generator wave I is the distal portion of the eighth nerve. Wave III is primarily generated by neurons in the cochlear nucleus with some additional contributions from fibers entering the superior olivary complex. Lastly, the neural origins of wave V are the lateral lemniscus and inferior colliculus. Researchers have proposed that there is no clear origin for each peak, but rather an overlap between each of the primary generator sites (Burkard & Don, 2015). The identification of the generator sites in humans was a major step in understanding these responses and provided a framework for the clinical interpretation of the ABR (Musiek et al., 2015). After the neural generators were identified, researchers began to study how the technical parameters of the ABR recording affect the response.

Technical Parameters of the Auditory Brainstem Response

The technical parameters of the ABR include the stimulus, recording, and subject-related parameters that are essential to successfully recording the ABR. The effects of these parameters on click and toneburst ABRs will be discussed further in this section of the literature review.

Stimulus-related effects of the Auditory Brainstem Response.

Various stimulus-related parameters affect the recording of the ABR in normal-hearing adults. These parameters include: stimulus type, stimulus rate, stimulus intensity, and stimulus polarity. Each of these stimulus parameters and their effects of click and toneburst ABRs will be examined below.

Effects of stimulus type.

Generally, the ABR is recorded to two different types of stimuli: clicks and brief tonebursts. A click is a stimulus brief in duration (e.g., 0/1 ms or 100 μs) that is comprised of a wide spectrum of energy (Picton, Stapells, & Campbell, 1981; Hall, 1991). Due to their unique properties, clicks stimulate a broad region of the basilar membrane when presented at high intensity levels (e.g. 80-90 dB nHL) (Picton et al., 1981; Hall, 1991). In a normal-hearing individual, a high intensity click will result in an ABR with easily identifiable waves I, III and V (Hall, 1991). High intensity clicks are recommended for recording otoneurologic ABRs because they evoke robust and detectable peaks and allow audiologists to evaluate the integrity of the auditory pathway from the VIII nerve to the level of the inferior colliculus.

Unlike click stimuli, a brief toneburst stimulus has energy at a single pure-tone frequency (e.g. 500 Hz) with some “spectral splatter” located above and below the characteristic frequency (Hall, 1991). This “spectral splatter” can also be defined as sidelobes. The toneburst stimulus activates the basilar membrane in the region surrounding the characteristic or target frequency, making it a more frequency-specific stimulus in comparison to the click stimulus. The brief tonal stimulus is the ideal choice for generating an ABR that reflects hearing sensitivity at a specific frequency (Hall, 1991). Therefore, brief tonebursts are generally used to estimate pure-tone audiograms in individuals who cannot be reliably tested using behavioral audiometry methods. Since the aim of this study is to collect otoneurologic ABR data for individuals with normal and conductive hearing loss, click stimuli will be employed.

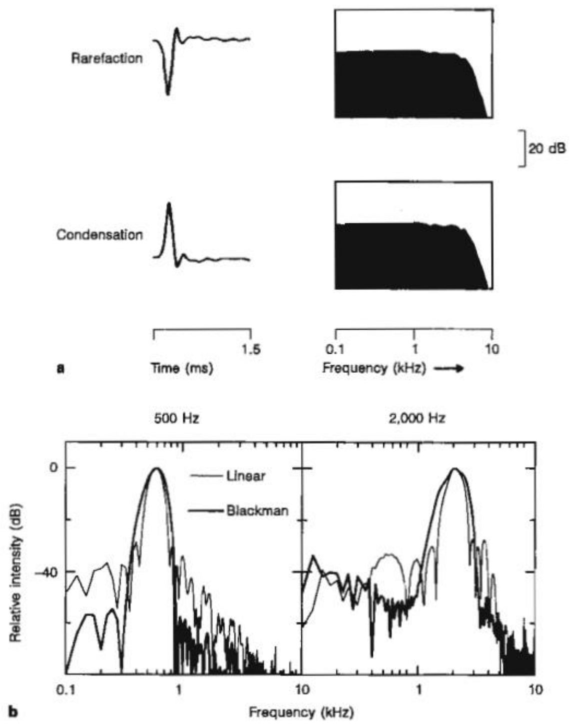

Figure 3. Acoustic spectra for rarefaction and condensation 100-µs clicks (**a**) and for 2-1-2 cycle 500 and 2000 Hz linear versus non-linear gated tones (**b**) (Stapells, Picton, & Smith, 1982; Oates, 1996).

Effects of stimulus rate.

Changes in the latency, amplitude, and morphology of the ABR have been observed in response to a change in the rate of presentation of the click or toneburst stimuli (Picton et al., 1981, Hood, 1998). As the rate of the stimulus is increased, there is an increase in latency and a decrease in amplitude of the response. However, this delay in latency and reduction in amplitude is not the same for all waves of the ABR. In general, the earlier waves (e.g. waves I and III) show a stronger decrease in amplitude when stimulus rate is increased in comparison to wave V. In contrast, the latency of wave V is more affected than the latency of the earlier waves when stimulus rate is increased. Numerous studies have examined specific latency and amplitude shifts of the ABR as a function of stimulus rate. Some of these studies have focused on the effect of rate change in click ABRs, while others have investigated the effects of rate change in toneburst ABRs. These studies will be discussed below.

Effects of stimulus rate on click-evoked ABRs.

In the 1980s, utilization of the ABR as a tool to estimate hearing was rapidly becoming part of the audiologist's clinical test battery. In order to determine the most efficient parameters for recording this response, researchers began to investigate the changes in the click-evoked ABR in response to different stimulus rates. In 1977, Weber and Fujikawa recorded click-evoked ABRs in 22 normal hearing adults (mean age 24.5 years) while using 3 different stimuli rates (13.3/sec, 33.3/sec, and 67/sec). All ABRs were recorded at a stimulus intensity of 60 dB SL (re: subjects' behavioral thresholds). These researchers only investigated the effects of stimulus rate on wave V latency and they reported mean wave V latencies of 5.84 ms, 5.90 ms, and 6.18 ms for stimulus rates of 13.3/sec, 33.3/sec, and 67/sec respectively. Results of Weber and Fujikawa's study demonstrated an increase in wave V latency with increased click stimulus rate (1977). As a result of these findings, these researchers emphasized that audiologists should have expected latency values/normative data available for each stimulus rate they utilize (Weber & Fujikawa, 1977).

In the same year, Don, Allen, and Starr also explored the effects of stimulus rate on the latency of wave V. The subjects in this study were 6 normal hearing adults, aged 18 to 34 years. The click stimuli were presented at 4 different stimulus rates (i.e., 10/sec, 30/sec, 50/sec, 100/sec) at several stimulus intensities. Specifically, at a stimulus intensity of 60 dB SL, mean wave V latencies increased from approximately 5.95 ms at 10/sec, 6.30 ms at 30/sec, 6.38 ms at 50/sec, to 6.60 ms at 100/sec. Similarly, at the lowest stimulus intensity (30 dB SL), wave V latency increased as stimulus rate increased from approximately 7.30 ms at 10/sec to about 8.10 ms at 100/sec. Don and colleagues reported that as the click rates increased there was an increase in the wave V latency at each stimulus intensity as seen in Figure 4 below. This same pattern occurred at each stimulus rate. Don and colleagues concluded that shifts in the latency of wave V in response to high stimulus rates could be used to assess adaptation in individuals with VIII nerve lesions (Don et al., 1977).

In order to understand the effects of stimulus rate on the entire ABR response, Yagi and Kaga measured the latency shifts of waves I, III, and V in response to six click rates: 5/sec, 10/sec, 30.3/sec, 50/sec, 71.4/sec, and 90.9/sec (1979). These researchers recorded click-evoked ABRs in 11 normal hearing adults (ages 19-32 years). The clicks were presented at a stimulus intensity of 70 dB nHL. Results revealed that the mean latency values of the later response component (e.g. wave V) increased more than the mean latency values of the earlier components (e.g. waves I and III) (Yagi & Kaga, 1979). For example, as stimulus rate was increased from 5/sec to 90.9/sec, mean wave I latency value increased by 0.4 ms, mean wave III latency value increased by 0.55 ms, and mean wave V latency value increased by 0.75 ms. Specific mean latencies of waves I, III, and V for all six repetition rates are displayed in Figure 5. Based on these findings, Yagi and Kaga concluded that the peripheral and central components of the auditory pathway differ in their responsiveness to repetitive stimuli (Yagi & Kaga, 1979).

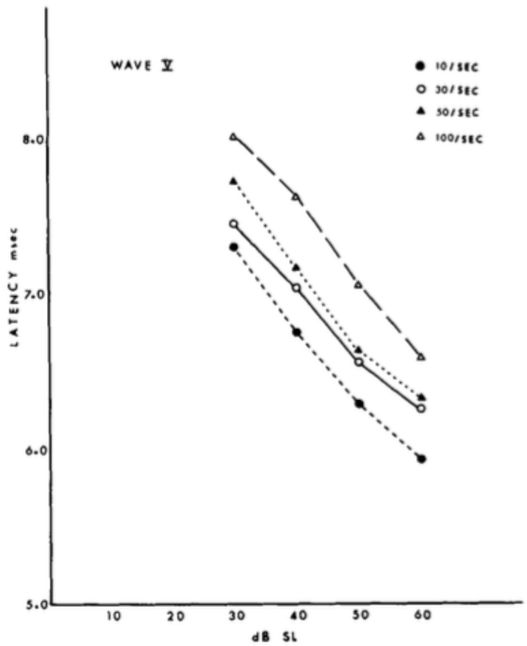

Figure 4. The mean latency of Wave V as a function of click intensity at four click rates in six normal hearing adults (ages 18-34) (Don, Allen, & Starr, 1977).

In order to further understand the peripheral versus central rate effects, Picton, Stapells, and Campbell (1981) studied the changes in the latency and amplitude of the ABR in response to clicks presented at stimulus rates ranging from 10 to 80 clicks per second. These researchers combined published results from many laboratories. As the researchers increased the stimulus rate from 10 to 80 clicks per second, the mean latency of wave I increased by approximately 0.14 ms, whereas the latency of wave V increased by approximately double that amount (0.39 ms). (Picton, Stapells, and Campbell, 1981).

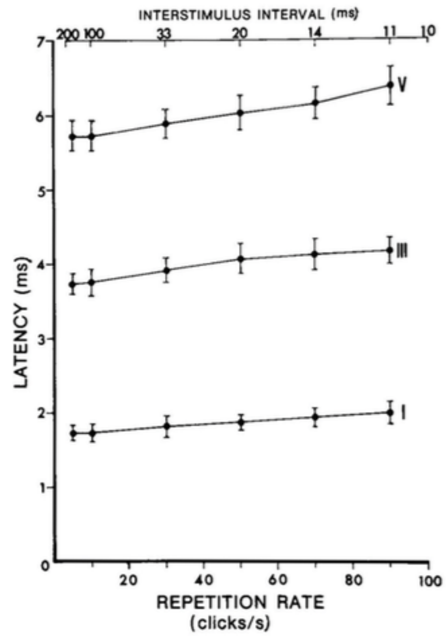

Figure 5. Mean latencies (filled circles) and standard deviations (bars) of waves I, III, and V in 11 normal hearing adults at a stimulus intensity of 70 dB nHL (Yagi and Kaga, 1979).

Similar to Yagi and Kaga's results, these findings suggested that stimulus rate has an increased effect on the central components of the auditory brainstem pathways. Picton and colleagues also reported that when stimulus rate was increased above 20 clicks per second, they observed a 50% reduction in the amplitudes of waves I and III, whereas the amplitude of wave V only decreased by 10-15% (Picton et al., 1981). Based on these findings, Picton and colleagues recommended using stimulus rates less than 20 clicks per second when recording the ABR to click stimuli for otoneurologic purposes in order to ensure present and robust waves I and III (Picton et al., 1981).

A few years later, Paludetti and colleagues (1983) studied the effects of stimulus rate on the amplitude and latency of click-evoked ABR waves in order to justify the possibility of using increasing stimulus rates as a test of the dynamic properties of the auditory brainstem (Paludetti, Maurizi, & Ottaviani, 1983). These researchers recorded click-evoked ABRs in 26 normal hearing males (ages 24-42 years) at four stimulus rates: 10/sec, 20/sec, 50/sec, and 100/sec. The click stimuli were presented at 70 dBnHL and the polarity of the stimuli were rarefaction. Paludetti and colleagues observed a mean latency shift of 0.45 ms for wave I; 0.52 ms for wave III; and 0.52 ms for wave V when the stimulus rate was increased from 10 to 100 clicks per second (Paludetti et al., 1983). Based on these results, these researchers recommended using a 50 clicks per second stimulus rate to test for retrocochlear pathologies as the ABR could be obtained in a more efficient fashion than the slower rates. Therefore, changes in the ABR waveform that appear when using a 50/sec stimulus rate can be suggestive of a retrocochlear pathology (Paludetti et al., 1983).

Similar to Paludetti and colleagues, Burkard and Sims studied the effects of stimulus rate on the amplitude and latency of the click-evoked ABRs in 11 normal hearing adults (ages 20-27 years) (2001). At a stimulus intensity of 115 dB pSPL, these researchers observed a mean latency shift of approximately 0.10 ms for wave I and 1.10 ms for wave V when the stimulus rate was increased from 11 to 500 clicks per second (Burkard & Sims, 2001). Additionally, the wave I-I' peak-to-peak amplitude decreased by 0.90 μV, while the wave V-V' amplitude decreased only by 0.44 μV when the stimulus rate was increased from 11 to 500 clicks per second (Burkard & Sims, 2001). This increase in ABR peak latencies and decrease in peak-to-peak amplitudes in response to increasing click rate agrees with the previous ABR literature on stimulus rate.

Collectively, the results of these click-evoked ABR studies suggest that increasing the stimulus rate above 20/sec can have a dramatic effect on the peak latencies and amplitudes of the ABR. When recording click-evoked stimulus otoneurologic ABRs, rates of less than 20 clicks per second are recommended (Picton et al., 1981; Hood, 1998).

Effects of stimulus rate on toneburst ABRs.

In addition to understanding the effect of stimulus rate on click-evoked otoneurologic ABRs, several studies have examined the effect of stimulus rate on toneburst ABRs. In 1979, Picton, Ouellette, Hamel, and Smith recorded ABRs to 500 Hz toneburst stimuli in five normal hearing participants. These researchers measured wave V absolute latencies and peak-to-peak amplitudes in all ABR recordings. 500 Hz tonebursts were presented at 76 dB nHL at rates of 4 to 5/sec and 40 to 50/sec. Continuous noise was presented simultaneously with the 500 Hz tonebursts. Picton and colleagues found that mean wave V peak-to-peak amplitude decreased from 0.63 μV to 0.50 μV as stimulus rate was increased from 4-5/sec to 40-50/sec, respectively. In contrast, these researchers did not measure any significant differences in wave V absolute latency as a function of stimulus rate. Based on this evidence. Picton and colleagues recommended that audiologists use slower stimulus rates when recording low frequency toneburst ABRs (i.e., 500 Hz in order to produce the most robust ABR wave V.

In 1981, Picton and Stapells conducted several experiments to examine various technical aspects of recording ABRs to tones, including stimulus rate. These researchers wanted to determine the optimal stimulation and recording parameters for recording toneburst ABRs (Picton & Stapells, 1981). At 110 dB pSPL, 500 Hz toneburst ABRs were recorded in 8 normal hearing adults (ages 22-30 years) at three different stimulus rates: 10/sec, 20/sec, and 30/sec (Picton & Stapells, 1981). These researchers observed mean wave V latencies of 8.50 ms, 9.50 ms, and 9.56 ms for these three stimulus rates, respectively. In addition, the researchers did not find a consistent change in the wave peak-to-peak V-V' amplitude with increasing stimulus rate (Picton & Stapells, 1981). Based on these results, Picton and Stapells recommended the use of a 35/sec stimulus presentation rate when recording auditory brainstem responses with tones. (Picton & Stapells, 1981).

Similar to Picton and Stapells' 1981 study, Parthasarathy and colleagues recorded ABRs to 250 Hz and 2000 Hz tonebursts in 10 healthy young adults at stimulus rates of 11.1/sec and 55.5/sec to investigate the effects of stimulus repetition rate on the wave V latency (Parthasarathy, Borgsmiller, & Cohlan, 1998). At a stimulus intensity of 75 dB HL, these researchers found a mean wave V latency shift of approximately 0.3 to 0.5 ms when the stimulus rate was increased from 11.1 to 55.5 stimuli/sec (Parthasarathy et al., 1998). Overall, Parthasarathy and colleagues reported that wave V latency changes with repetition rate were independent of stimulus frequency.

Together, the results of these studies show increased ABR absolute latencies and decreased peak-to-peak amplitudes in response to increased stimulus rates. When recording toneburst ABRs, a stimulus presentation rate of 35/sec is recommended (Picton & Stapells, 1981). In the proposed study, a stimulus presentation rate of 19.1 clicks/sec will be employed to record otoneurologic click-evoked ABRs in normal hearing participants.

Effects of stimulus intensity.

Similar to stimulus rate, latency, amplitude, and morphology changes occur in response to changes in stimulus intensity (Picton et al., 1981, Hood, 1998). As the intensity of the stimulus is decreased, increases in latency and decreases in amplitude are observed. However, this decrease in amplitude is not the same for all waves of the ABR. In general, the earlier waves (e.g. waves I and III) show a stronger decrease in amplitude when stimulus intensity is decreased in comparison to wave V. Wave V is often the only observable wave as stimulus intensity approaches threshold. Numerous studies have examined specific latency and amplitude shifts of the ABR response as a function of stimulus intensity. Some of these studies have focused the effect of intensity change in click ABRs while others have investigated the effects of intensity change in toneburst ABRs. These studies will be discussed below.

Effects of stimulus intensity on click-evoked ABRs.

In 1977, Weber and Fujikawa studied the effects of stimulus intensity by recording click-evoked ABRs in 22 normal hearing adults (mean age 24.5 years). These researchers presented clicks at 7 different intensities ranging from 10 to 60 dB SL. These researchers found an increase in the latency of wave V as stimulus intensity was decreased. For instance, as the stimulus intensity was decreased from 60 dB SL to 10 dB SL, the mean latency of wave V increased from 5.84 ms to 7.87 ms, respectively (Weber & Fujikawa, 1977). These researchers also reported less variability between participants' wave V latencies at higher stimulus intensities. Based on these findings, Weber and Fujikawa concluded that hearing status of participants could be closely estimated using wave V latencies. In order to do this in the future, these researchers strongly suggested the need for normative latency data at each stimulus intensity.

Similar to Weber and Fujikawa, Don, Allen, and Starr measured the latency of wave V as a function of four different stimulus intensities; 30, 40, 50, and 60 dB SL (1977). These researchers presented clicks to six normal hearing adult subjects, aged 18 to 34 years. Results showed a decrease in the latency of wave V as the intensity of the click was increased, which was evident at all click rates (as seen in Figure 3). Specifically, these researchers measured approximately a 0.40 ms decrease in latency for every 10 dB increase in click intensity (Don, Allen, & Starr, 1977). For example, the mean latency of wave V decreased from 5.95 ms at 60 dB SL to 6.30 ms at 50 dB SL. Don, Allen, and Starr concluded that wave V of click-evoked ABRs can be detected close to hearing thresholds which allows researchers to use far field auditory brainstem responses to determine the integrity of the auditory system in humans (1977).

One year later, Wolfe, Skinner, and Burns further studied the effects of stimulus intensity on the click-evoked ABR by measuring the latency of all waves of the ABR (i.e. I-VII) (1978). Wolfe and colleagues presented clicks to five male undergraduate students at 6 different stimulus intensities (20, 30, 40, 50, 60, 70 dB SL). These researchers observed decreases in mean latency values for all seven waves in response to increased stimulus intensity (as seen in Table 1). However, these researchers noted that wave V was the most prominent and consistent of the ABR components. All seven waves were present and identifiable at intensity levels of 40 dB SL and greater (Wolfe, Skinner, & Burns, 1978). Although Wolfe and colleagues mainly focused on the relationship between stimulus intensity and wave V latency, they concluded that peak amplitude is also an important criterion in the detection of the click-evoked ABR and should be used to evaluate the response signal (1978).

Table 1

Group Means and Standard Deviations for Latency (ms) of Each ABR Wave with Increasing Sensation Levels (Wolfe, Skinner, & Burns, 1978)

		dB Sensation Level					
Wavelet		*20*	*30*	*40*	*50*	*60*	*70*
I	Mean	1 38	2 09	1 57	1 23	0 93	0 84
	SD	0 74	0 47	0 54	0 37	0 31	0 30
II		2 35	3 18	2 49	2 05	1 97	1 96
		0 77	0 52	0 61	0 48	0 34	0 25
III		4 08	3 96	3 48	3 09	3 11	2 96
		0 97	0 61	0 65	0 48	0 38	0 25
IV		5 60	5 11	4 46	4 02	4 05	4 17
		0 63	0 55	0 64	0 53	0 46	0 23
V		6 67	5 99	5 56	5 27	4 98	4 79
		0 42	0 28	0 47	0 64	0 46	0 29
VI		8 34	7 81	7 46	7 03	6 92	6 47
		1 70	0 27	0 40	0 45	0 53	0 28
VII		10 00	9 90*	9 20	9 26	8 69	8 28
		0 57	–	0 83	0 24	0 65	0 29

*Wavelet VII latency was based on four subjects

In order to further understand the effects of changing stimulus intensity, Stockard and colleagues measured the latencies of waves I, III, and V to click-evoked ABRs (1979). Sixty-four normal hearing adults (ages 18-75 years) participated in the study and these researchers measured click-evoked ABRs to five different stimulus intensities, ranging from 30 to 70 dB SL (Stockard, Stockard, Westmoreland, & Corfits, 1979). Results showed an increase in the mean peak latencies of all waves with a decrease in stimulus intensity. However, the magnitude of this latency increase was different for the earlier versus later components of the ABR. The magnitude of the latency shift was greater for wave I than for later components. Additionally, these researchers found that the shifts in latency were nonlinear. Stockard and colleagues concluded that wave I was impacted more by decreased stimulus intensity than the later components of the ABR because wave I is generated by the eighth nerve action potential. Therefore, as stimulus intensity is decreased, the action potential is triggered in more apical regions of the cochlea, which increases travel time along the basilar membrane. This ultimately results in a delayed absolute wave I latency (Stockard et al., 1979).

A few years later, Picton, Stapells, and Campbell (1981) combined reported results from many different laboratories to study the effects of stimulus intensity on both the latency and amplitude values of the various ABR waves. These researchers reported latency increases and amplitude decreases in all components of the click-evoked ABR in response to decreased stimulus intensity. These distinctive latency and amplitude trends for wave V can be observed in Figure 6 below. Similar to Stockard and colleagues, these researchers reported a slightly larger latency shift for wave I in comparison to wave V when decreasing stimulus intensity (Picton, Stapells, & Campbell, 1981). Although these researchers note that it is difficult to compare amplitude data across laboratories because of differing high-pass filter settings, they found that earlier components (i.e. wave I) of the click-evoked ABR show a more rapid amplitude reduction in response to decreased stimulus intensity than the later components (i.e. wave V). These researchers concluded that wave V is easily detectable in normal hearing individuals within 20 dB of threshold, whereas the earlier components of the ABR (i.e. waves I and III) become difficult to recognize and identify below 50 dB nHL (Picton, Stapells, and Campbell, 1981).

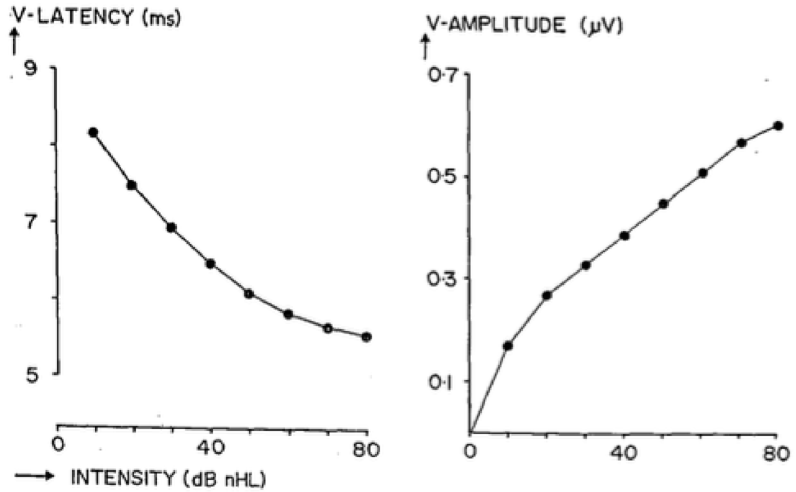

Figure 6. Average peak-latencies and amplitudes for wave V. Data were obtained by combining results from many different laboratories. (Picton, Stapells, and Campbell, 1981).

In 1989, Gerling recorded click-evoked ABRs in 19 normal hearing adults (ages 21-31 years) at two different stimulus intensities: 50 dB nHL and 80 dB nHL. When decreasing the stimulus intensity from 80 dB nHL to 50 dB nHL, Gerling measured mean wave V latencies of 5.66 ms and 6.64 ms, respectively. These researchers also observed a significant reduction in the wave V amplitude in 4 of the 19 subjects. However, this phenomenon only occurred at a low stimulus rate for all 4 participants. Ultimately, Gerling determined that a significant reduction in the wave V amplitude following a decrease in stimulus intensity was dependent upon other stimulus factors like phase and rate (1989). This significant decline in amplitude was only seen when a rarefaction click was presented at a low stimulus rate (Gerling, 1989).

Collectively, the results of these studies demonstrated that ABR wave absolute latencies increase in response to decreasing stimulus intensity. Additionally, ABR wave peak-to-peak amplitudes decrease in response to decreasing stimulus intensity. Ultimately, high stimulus intensities should be employed when recording click-evoked ABRs in order to record the shortest absolute latencies and largest peak-to-peak amplitudes. In the proposed study, an initial stimulus intensity of 80 dB nHL for the click stimulus will be employed to ensure that the various peaks in the response can be clearly identified. Then stimulus intensity will be decreased to establish the ABR threshold for the normal hearing control group as well as for the simulated conductive hearing loss group.

Effect of stimulus intensity on toneburst ABRs.

In addition to understanding the effect of stimulus intensity on click-evoked otoneurologic ABRs, several studies have examined the effect of stimulus intensity on toneburst ABRs. First, Stapells and Picton (1981) evaluated the effects of different stimulus intensities (70, 90, and 110 dB peak SPL) on the ABR to 500 Hz toneburst presented at varying stimulus rates and different high-pass filter settings. These researchers measured wave V latencies and amplitudes in the toneburst ABRs of eight normal hearing adults (ages 22-30 years). Results showed that decreasing the stimulus intensity caused an increase in wave V latency and a decrease in the peak-to-peak wave V amplitude at all filter settings and stimulus presentation rates (Stapells & Picton, 1981). Specifically, when the toneburst was presented using a high pass filter setting of 10 Hz and a 10/sec stimulus rate, the mean wave V latencies were 8.72 ms at 110 dB peak SPL, 9.68 ms at 90 dB SPL, and 12.37 ms at 70 dB SPL. Similarly, the mean wave V-V’ peak-to-peak amplitude measurements at 10/sec were 0.63 μV, 0.45 μV, and 0.32 μV at 110, 90, and 70 dB peak SPL, respectively (Stapells & Picton, 1981). Overall, Stapells and

Picton concluded that when stimulus intensity was decreased, wave V showed increases in latency and decreases in amplitude at all high-pass filters and stimulus rates (as seen in Figure 7).

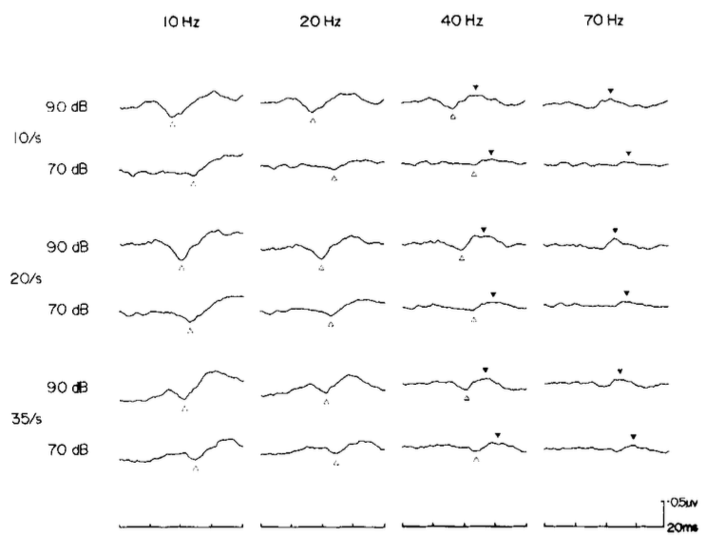

Figure 7. Effects of high-pass filter settings and stimulus presentation rate on the response to 500 Hz tones. Waveforms are the average of 4000 responses from one individual. Wave V is represented with a white triangle and V' component is represented with a filled-in black triangle (Stapells & Picton, 1981).

Effects of stimulus polarity.

There are three different stimulus polarity choices for an ABR: rarefaction, condensation, or a stimulus that alternates between rarefaction and condensation (alternating). A rarefaction stimulus produces an initial outward movement of the diaphragm of the transducer and an initial negative electrical pulse. This leads to an outward movement of the stapes and an upward motion of the cochlear partition (Hood, 1998). This upward deflection of the basilar membrane activates the afferent auditory neurons. On the contrary, a condensation stimulus produces an initial inward movement of the diaphragm of the transducer and an initial positive electrical pulse. This leads to a negative deflection of the basilar membrane (Hood, 1998). Several studies have examined specific latency and amplitude shifts of the ABR as a function of stimulus polarity. Some of these studies have focused the effect of polarity in click ABRs while others have investigated the effects of polarity in toneburst ABRs. These studies will be discussed below.

Effects of stimulus polarity on click-evoked ABRs.

In addition to investigating the effects of stimulus intensity, Stockard et al. (1979) studied the effects of stimulus polarity in order to establish optimal techniques for recording the ABR. These researchers recorded click-evoked ABRs in 64 normal hearing adults (ages 18-75 years) with 2 different stimulus polarities: rarefaction and condensation. In response to a rarefaction click, these researchers recorded mean latencies of 1.62 ms, 3.75 ms, and 5.62 ms for waves I, III, and V, respectively. In contrast, a condensation click produced mean latencies of 1.69 ms, 3.77 ms, and 5.64 ms for waves I, III, and V (Stockard et al., 1979). Stockard and colleagues found that the peak latency of wave V was least affected by the inversion of stimulus phase. In most cases, these researchers found that rarefaction clicks produced an earlier wave I latency in comparison to condensation clicks (Stockard et al., 1979). Additionally, the results showed that wave IV was more prominent in rarefaction ABRs, while wave V was enhanced by the use of condensation clicks. Lastly, wave I amplitude was also larger in the majority of rarefaction recordings. Ultimately, Stockard and colleagues suggested that both rarefaction and condensation clicks should be used in order to clearly identify all components of the ABR (Stockard et al., 1979).

Similar to Stockard et al. (1979), Picton and colleagues combined published results from many laboratories to better understand how stimulus polarity affects the ABR. These researchers reported that there were changes in latency of waves I, III, and V in response to both rarefaction and condensation clicks within the same individual. For example, they reported that one normal hearing individual had latencies of 1.40 ms for wave 1, 3.30 ms for wave III, and 5.60 ms for wave V in response to a rarefaction click presented at 80 dB nHL (Picton, Stapells, & Campbell, 1981). In contrast, the same individual had latencies of 1.90 ms for wave I, 3.90 ms for wave III, and 6.10 ms for wave V in response to the same intensity condensation click. By combining the published results from several laboratories, these researchers reported that rarefaction clicks generally produced a wave I with shorter latency and larger amplitude in comparison to a response to a condensation click (Picton, Stapells, and Campbell, 1981). Additionally, they found that the latency and amplitude of waves III and V were not significantly affected by the polarity of the click stimulus. Overall, Picton and colleagues determined that there are small, but significant changes between rarefaction and condensation click-evoked ABRs (1981).

A few years later, Gerling (1989) further investigated the effects of stimulus polarity by examining click-evoked ABRs to three different stimulus polarities: rarefaction, condensation, and alternating. Gerling measured wave V latency changes in response to the various stimulus polarities in eight normal hearing male adults. Results showed little to no change between the responses to the three different stimulus polarities. Specifically, their mean wave V latencies were 5.65 ms for rarefaction, 5.55 ms for condensation, and 5.55 ms for alternating. In contrast to previous studies, Gerling did not find a definitive relationship between stimulus polarity and wave V latency. Therefore, Gerling (1989) recommended that clinicians remain flexible and use a stimulus with either a single or alternating polarity whenever it is appropriate. Additionally, Gerling suggested that clinicians be familiar with normal variations that occur when altering stimulus parameters in order to properly interpret the ABR.

In order to further understand the impact of stimulus polarity on the click-evoked ABR, Patricio de Lime and colleagues (2008) investigated the effect of stimulus polarity on the latencies of waves I, III, and V. These researchers presented clicks at 80 dB nHL to33 normal hearing individuals (ages 18-28 years) and varied the stimulus polarity between rarefaction, condensation, and alternating. Results showed that wave I, III, and V latency values were generally shorter for responses to rarefaction polarity clicks in comparison to responses for both condensation and alternating polarity clicks. This distinctive trend was most significant in wave V, with a 0.14 ms difference between rarefaction and condensation polarities and a 0.10 ms difference between rarefaction and alternation polarities. Overall, de Lime and colleagues concluded that click polarity significantly impacts the absolute latencies of waves I, III, and V, with the largest differences seen for rarefaction clicks. With insertion ER3A earphones, the researchers suggested using simple polarities (rarefaction and condensation) when recording click-evoked ABRs in order to measure the cochlear microphonic for accurate auditory neuropathy diagnosis.

In 2015, Gução et al. recorded click-evoked ABRs to characterize and compare the effects of different polarity variations: rarefaction and condensation. At a high stimulus intensity (80 dBNAn), these researchers measured the absolute latencies of waves I, III, and V in 22 normal hearing females (ages 15-30 years). In general, these researchers found that the absolute latencies of all waves were shorter in response to rarefaction clicks in comparison to responses to condensation clicks. Based on their results, Gução and colleagues (2015) recommended using variations in the polarity of the click stimulus in order to assist in the detection of pathologies and hearing.

Together these studies found that there are differences in the absolute latencies of ABR waves I, III, and V in response to rarefaction and condensation polarity clicks. Overall, researchers suggested using alternating polarity clicks in order to obtain both rarefaction and condensation ABR recordings. The rarefaction and condensation ABR recordings can then be used together for ABR analysis. In the proposed study, we will be recording the click ABRS to alternating polarity stimuli. Given the flexibility of the Intelligent Hearing System's Smart EP platform, the responses to the alternating stimuli can be separated into their single polarity responses if needed.

Effects of stimulus polarity on toneburst ABR

In addition to understanding the effect of stimulus polarity on click-evoked otoneurologic ABRs, several studies have examined the effect of stimulus polarity on toneburst ABRs. In 1991, Gorga and colleagues examined the effect of stimulus polarity on wave V latency in five normal hearing young adults (Gorga, Kaminski, & Beauchaine, 1991). These researchers presented rarefaction polarity and condensation polarity tonebursts at four different stimulus frequencies: 250 Hz, 500 Hz, 1000 Hz, and 2000 Hz. At a high stimulus intensity (90 dB SPL), results showed shorter mean wave V latencies for rarefaction polarity tonebursts compared to condensation polarity tonebursts at both

250 Hz and 500 Hz. In contrast, at 1000 Hz and 2000 Hz, no significant wave V latency differences were recorded for rarefaction and condensation tonebursts.

Similar to Gorga and colleagues, Parthasarathy et al. (1998) studied the effects of stimulus polarity on toneburst ABRs in ten normal hearing young adults. Partharsarathy and colleagues recorded both rarefaction and condensation ABRs in response to 250 and 500 Hz stimuli. These researchers measured mean wave V latencies for all test conditions. For both 250 and 2000 Hz stimuli, these researchers measured shorter latencies for the rarefaction polarity compared to the condensation polarity. Specifically, at 250 Hz mean wave V latencies were approximately 7.70 ms and 8.50 ms for rarefaction and condensation polarities, respectively. Similarly, at 2000 Hz mean wave V latencies were approximately 6.70 ms and 6.85 ms. While mean wave V latencies for rarefaction were shorter than condensation for 250 and 2000 Hz, the difference between mean wave V latency was only significant for the lower frequency (250 Hz). Overall, Parthasarathy and colleagues concluded that large ABR wave V differences occur as a result of stimulus phase reversal for low-frequency stimuli like 250 Hz.

Collectively, these studies showed large ABR wave V latency differences for low frequencies such as 250 Hz and 500 Hz. Rarefaction polarity produces shorter wave V latencies than condensation polarity. In contrast, no significant wave V latency differences were measured between rarefaction and condensation tonebursts for higher frequencies like 1000 Hz and 2000 Hz. Ultimately, rarefaction or alternating stimulus polarities are recommended when recording toneburst ABRs in normal hearing individuals.

Similar to the effects of the technical parameters (rate, intensity, polarity) on click-evoked and toneburst ABRs, there are several recording parameters that can affect the ABR. These parameters will be discussed in detail in the section below.

Recording parameters of the auditory brainstem response.

There are various recording parameters that can affect the ABR. These parameters include: EEG bandpass filter settings, length of post-stimulus analysis window, number of sweeps, artifact rejection rate, and electrode montage. Each of these recording parameters will be briefly discussed below in regard to their effects on the click and toneburst ABR.

Effects of analog bandpass filter setting on the ABR.

The purpose of using an analog bandpass filter when recording the ABR is to remove as much of the ongoing EEG background noise and unwanted electrical activity as possible without affecting the frequency range of the desired evoked potential (Hood, 1998). When obtaining an ABR, choosing the appropriate analog bandpass filter settings is crucial.

In order to determine the correct analog bandpass filter settings for the ABR, Suzuki and colleagues investigated the primary frequencies present in the ABR (Suzuki, Sakabe, & Miyashita, 1982). These researchers presented tonal stimuli (1000, 2000, and 4000 Hz) to three normal hearing adults at both 40 and 80 dB SL. Responses were analyzed with Fast Fourier Transform (FFT) to determine the frequencies in which the primary peaks of energy existed in the ABR. Suzuki and colleagues found three prominent peaks of energy in the recordings to tonal stimuli at 80 dB SL. These peaks of energy were present at 50-150 Hz, 500-600 Hz, and 1000-1100 Hz. At this high stimulus intensity (80 dB SL), the greatest amount of energy came from the lowest peak, which contained energy below 250 Hz (Suzuki et al., 1982).

Additionally, Suzuki and colleagues found that as stimulus intensity decreased, the peak energy in the response shifted to lower frequency regions. When stimulus intensity was decreased to 40 dB SL, the peaks of energy at 500-600 Hz and 1000-1100 Hz decreased in magnitude in comparison to energy present in response to the high intensity stimulus (80 dB SL) (Suzuki et al., 1982). For otoneurologic ABRs conducted using high intensity click stimuli, a bandpass filter setting of 100-3000 Hz is recommended to accurately capture the energy present in this response. In contrast, when recording the ABR using toneburst stimuli, especially at the lower frequencies (i.e., 500 and 1000 Hz), analog bandpass filter settings of 30-3000 Hz are recommended to emphasize wave V and effectively capture the low frequency energy present in the response especially at low stimulus intensities (Hood, 1998).

In addition to the bandpass filter settings, the slope of the filter can also affect the ABR recording. In 1984, Elton, Scherg, and Von Cramon examined the effects of analog filter slopes on the ABR. In 20 normal hearing individuals, these investigators increased the slope of the filter from 6 dB/octave to 24 dB/octave in 6 dB steps. Results showed that filter slopes less than or equal to 12 dB/octave created the least amount of distortion in the ABR recording. Additionally, slopes greater than 12 dB/octave produced significant delays in latencies and reductions in amplitudes of wave I, III, and V. Therefore, Elton and colleagues recommended using analog bandpass filter slopes less than or equal to 12 dB/octave when recording the ABR in order to minimize the distortion in the morphology of the response (Elton, Scherg, & Von Cramon, 1984). In the proposed study, the analog bandpass filter will be set to 30-3000 Hz and will have a 12 dB/octave filter slope.

Effect of length of post-stimulus analysis window.

The length of the post-stimulus analysis window, in milliseconds, is critical when recording the ABR. The analysis time window should be set to encompass all of the components of the response (Hood, 2015). A high intensity click stimulus produces a traveling wave that is propagated along the basilar membrane within 2 to 5 seconds post-stimulus onset (Picton et al., 1981). As a result, wave V of the ABR occurs within 5 to 6 ms of a stimulus at high stimulus intensities and within 8 to 9 ms for a low intensity stimulus (Hood, 1998). Therefore, a post-analysis time window of 10 to 12 ms is recommended for otoneurologic ABRs (Hood, 1998). Although a 10 to 12 ms post-stimulus analysis window is sufficient when recording click-evoked ABRs, toneburst ABR testing requires a time window of at least 20 ms (Hood, 1998). This is especially important when using 250 and 500 Hz tonebursts where the stimuli have longer onset times and activate more apical regions of the cochlea (Hood, 1998). Since this study will be recording ABRs to click stimuli in young adults with normal hearing sensitivity, a post-stimulus analysis window of 12.8 ms will be used.

Effect of the number of sweeps.

The ABR recording is too small to recognize in the presence of other background noise, such as muscle artifact, 60-Hz noise, and electroencephalographic (EEG) activity (Hood, 1998). In order to separate the desired neural signal from the other background noise, a series of time-locked responses, or sweeps, are averaged together. The number of sweeps is the amount of stimuli presented for one averaged waveform (Stapells & Oates, 1997). Ultimately, as the number of sweeps is increased, the amplitude of the desired ABR recording will remain constant, while the amplitude of the competing background EEG noise will decrease. This increase in sweep/count results in an improved signal-to-noise ratio (SNR). Researchers have recommended an SNR of at least 2:1 to record a clear and replicable ABR for otoneurologic purposes (Picton, Linden, Hamel, & Maru, 1983; Stapells, 1989). In order to increase the SNR of the ABR, the number of sweeps averaged together and the number of replications should be increased. Picton, Linden, Hamel, and Maru (1983) recommended at least 1600 total sweeps in order to obtain an SNR of 2:1.

In addition to increasing the number of sweeps, replicating the ABR response 2 or more times can enhance the signal to noise ratio (Hood, 1998). In contrast to number of sweeps, number of replications is the number of times an averaged waveform is completed (Stapells & Oates, 1997). In the proposed study, each waveform will have a total of 1,024 sweeps. Additionally, each run will have at least 2 replications, for a total of at least 2,048 sweeps per test condition.

Effect of artifact rejection.

Another method of decreasing the effects of background noise on the ABR is changing the artifact rejection criterion level. While recording the ABR, sweeps may contain excessive levels of background noise. Consequently, the background noise affects the ongoing averaging so that the ABR amplitude is reduced and response is hard to recognize (Don & Elberling, 1994). In order to prevent excessive noise from impacting the response, clinicians can set artifact rejection criteria to discard sweeps containing voltage levels greater than the neural signal of interest (Hood, 1998; Katz, 2015).

However, if the rejection criteria is set at too strict a criteria, a large number of sweeps may be omitted from the waveform. These omissions can lead to a high number of total sweeps, which can cause test time to increase (Don & Elberling, 1994). For the ABR, which is in the voltage range of 0.1 to 1.0 μV, a typical artifact rejection level might be 10 μV (Hood, 1998). However, most ABR studies have successfully used artifact rejection criterion of ± 25 μV to reduce competing background noise without significantly increasing test time (Don & Elberling, 1994). Therefore, in the proposed study, we will employ a ± 25 μV artifact rejection criterion.

Effect of electrode montage and number of recording channels.

The ABR is recorded by attaching electrodes to various locations on the scalp using surface electrodes. These surface electrodes are placed on the scalp according to the 10/20 electrode system created by Jasper in 1958. The 10/20 electrode system created a standardized and universal system of electrode placement on the scalp that ensured similar placement among individuals with different size skills (Jasper, 1958).

According to the 10/20 system, electrode locations were named based on their anatomical scalp locations as well as the placement on the head. A letter system is used to signify the anatomical scalp location in relation to the lobes of the brain. For instance, an uppercase “F” denotes the frontal lobes; an uppercase “C” refers to the coronal line; an uppercase “P” stands for the parietal lobe, and an uppercase “A” or “M” refer to the aurus (earlobe) or mastoid, respectively. In addition to a letter referring to the anatomical scalp location, a number is used to further delineate the electrode location on the head. Electrode locations on the left side of the scalp are referred to with odd numbers, electrode locations on the right side of the scalp are referred to with even numbers, and an electrode placement along the midline is marked with a lowercase “z”. For example, when an electrode is placed in the midline position in the frontal lobe area, it would be labeled Fz.

Two-channel recordings, using a four-electrode montage, are used most often when recording the ABR in order to obtain both ipsilateral and contralateral responses (Hood, 1998). Recording two channels simultaneously gives the clinician information from both recording channels which often helps to more accurately identify the ABR waves. Typically, wave I is more robust in the ipsilateral channel than the contralateral channel. However, the contralateral channel provides a better separation of waves IV and V. With a two-channel recording, the audiologist can better measure and define each wave of the ABR.

In the proposed study, the electrode placement for the ipsilateral and contralateral recording channels will be as follows: a non-inverting or active electrode is placed at Cz. According to multiple studies, this placement results in the greatest wave V amplitude (Beattie & Lipp, 1990; Beattie & Taggart, 1989; Terkildsen & Osterhammel, 1981). The inverting or reference electrodes will be pleased on the test earlobe for the ipsilateral recording and the opposite earlobe for the contralateral recording. Lastly, the ground electrode will be placed on the forehead at Fpz.

In addition to electrode montage on the scalp, impedance values (in ohms) at each electrode site as well as impedance values between electrode sites need to be considered. In order to reduce the level of electrical noise present in the response, an impedance level for each electrode of less than 5000 ohms should be used (Hall, 2007; Hood, 1998). There should also be fairly equal impedance, less than 2000 ohms, between all electrode sites. Fairly equal electrode impedance values help to minimize background electrical noise and interference as well as increase the efficiency of the common mode rejection system (Hall, 2007; Hood, 1998). Therefore, in the proposed study, all electrode sites will have impedance values <5000 ohms and the inter-impedance values between electrode sites will be <2000 ohms.

In addition to the various recording parameters that can affect the ABR recording, there are numerous subject-related factors that can affect the ABR. These subject-related factors will be discussed in the next section of the literature review.

Subject-related factors affecting the ABR

There are various subject-related factors that can influence the ABR. These factors include subject state, age, and gender. Each of these factors will be briefly discussed below.

Effects of subject state on the ABR.

Several studies have investigated the effects of sleep on ABR recordings. In 1985, Osterhammel, Shallop, and Terkildsen studied the effects of natural sleep on both the ABR and MLR. These researchers recorded click-evoked ABR and MLR responses in four adults at two different stimulus intensities: 60 and 30 dBnHL. ABR and MLR recordings were acquired throughout the night while the patients were sleeping. The subjects' actual stages of sleep were monitored throughout the night. This allowed the researchers to determine the effects of various sleep stages on the response properties of ABR and MLR and compare them to their response obtained while awake. Osterhammel and colleagues (1985) reported no significant changes in the amplitudes or latencies of the various waves of the ABR as a function of sleep stage. In contrast, the MLR showed an overall reduction in amplitude and increase in latency in sleep in sleep stages 3 and 4.

Several other researchers were interested in determining the effect of pharmacologically induced sleep, or sedation, on the ABR recording. Numerous studies have shown that most of the commonly used sedatives, such as nitrous oxide/halothane anesthesia and barbiturate, have no significant effect on ABR latency or amplitude (Sanders, Duncan, McCullough, 1979). Therefore, otoneurologic and threshold ABRs can be completed under sedation in difficult to test populations without any effect on the ABR recording.

Since natural sleep has been shown to have no significant effect on the ABR recording, participants in the proposed study will be instructed to relax and sleep if possible during the testing. No pharmacological agents or sedatives will be given to the participants in the proposed study.

Effects of age on the ABR.

The age of the participant can affect the latency and amplitude of the ABR recording. These age-related effects can be seen when comparing infants and young children responses to those obtained from older adults. In 1974, Hecox and Galambos conducted a study to compare the ABR of infants/children (ages 3 weeks to 3 years) to that of adults. Results showed an increase in the latency of wave V seen in the infants until they reached approximately 12-18 months of age. At 12-18 months, the ABR waveform begins to closely resemble the adult ABR recording (Hecox & Galambos, 1974).

Similarly, there are age-related differences in ABR waveforms recorded from younger adults and older adults (Konrad-Martin et al., 2012). In 2012, Konrad-Martin and colleagues investigated these age effects in 131 participants aged 26 to 71 years. These researchers recorded ABRs to click stimulus presented at three different stimulus rates: 11/sec, 51/sec, and 71/sec. The researchers compared age differences in ABR recordings at each click rate. Konrad-Martin and colleagues reported an increase in latency and a reduction in amplitude for waves I, III, and V as the participant's age increased. Although the age effect was most prominent at the slowest click rate (11/sec), similar latency shifts between younger and older adults were recorded at all stimulus rates. In the proposed study, adults with normal hearing between the ages of 18 to 25 years will be recruited in order to control for any effects of aging on the ABR.

Effects of gender on the ABR.

Several studies have demonstrated significant differences in the amplitudes, latencies, and interpeak latencies of the ABR between males and females (Jerger & Hall, 1980; Kjaer, 1979). Typically, females have large amplitudes, shorter latencies, and shorter interpeak latencies in comparison to males (Jerger & Hall, 1980; Kjaer, 1979).

In 1979, Kjaer investigated the specific ABR differences between genders. He recorded click-evoked ABRs in 21 females and 19 males with normal hearing (13-48 years). He presented clicks at 75 dB HL and measured the latency and amplitude of ABR waves I-VII. Results showed increased absolute latency values for all ABR waves measured in males compared to females (Kjaer, 1979). This increase in absolute latency was more pronounced for the later waves (e.g. IV-VII). Additionally, Kjaer recorded significantly larger amplitudes for waves I, III, and V in female participants in comparison with male participants.

There have been several potential causes proposed for these gender differences in the ABR recordings. Specifically, researchers have investigated the effect of differences in core body temperatures and head sizes between men and women on the ABR. Although males have higher average core temperature by ~3 degrees Celsius, Hall (2007) reported that this small difference in body temperature is not enough to produce latency and amplitude differences between males and females. Only extreme body temperatures, such as hypothermia and hyperthermia, have the ability to cause differences in ABR recordings (Hall, 2007).

Head size was also considered a potential cause for the differences between male and female ABR recordings. In 1986, Dempsey, Censoprano, and Mzor compared latencies and amplitudes of wave V in males and females. Dempsey and colleagues found that even when males and females were matched for head size (128.5 cm), males still exhibited longer wave V latencies and larger amplitudes in comparison to females. These researchers concluded that regardless of gender, absolute latency of wave V will increase as head size increases.

Following these investigations, Don, Ponton, Eggermont, and Masuda (1994) completed a study to determine the possible physiological reasons for these ABR gender differences. Don and colleagues speculated that shorter cochlear response times may be responsible for shortened latencies in females. Don et al. (1994) found that cochlear response times in females are 13% shorter than that of males. Additionally, these researchers reported a steeper gradient in the female cochlea, which contributes to shorter absolute latencies.

In order to control for gender effects on the ABR response in the proposed study, an approximately equal number of males and females will be recruited to participate.

In addition to the various technical parameters (stimulus, recording and subject-related), conductive hearing loss can have a significant impact on the ABR recording. The specific effects of conductive hearing loss on click and toneburst ABRs will be discussed further below.

Effects of Conductive Hearing Loss on the ABR

Conductive lesions impair the transmission of sound from the environment to the cochlea (Gelfand, 2016). As a result, the auditory system receives a weakened signal. Conductive hearing loss is the degree by which the signal is weakened due to the lesion and is expressed by an air-bone gap (Gelfand, 2016). For instance, a 30 dB conductive hearing loss means that the sound reaching the cochlea is 30 dB weaker than it would have been if the auditory system had been functioning normally.

In addition to attenuating the signal that arrives at the cochlea, conductive hearing loss affects the ABR recording. In general, conductive hearing loss causes a prolongation in the absolute latencies of all ABR waves (Hood, 1998). However, interpeak latencies remain within normal limits (Hood, 1998). The shift in latency of the entire ABR waveform occurs as a result of the attenuation in the auditory signal arriving at the cochlea. Numerous studies have examined specific latency shifts of the ABR as a function of conductive hearing loss in adults. Some of these studies have focused the effect of conductive hearing loss on click ABRs while others have investigated the effects of conductive hearing loss on toneburst ABRs. These studies will be discussed below.

In 1982, McGee and Clemis compared ABRs from 22 normal-hearing subjects and 23 patients with various conductive disorders. Ages of the participants ranged from 3 to 76 years. These disorders included occluded external auditory canal, middle ear effusion, otosclerosis, and various ossicular chain disorders (McGee & Clemis, 1982). For each patient with a conductive hearing loss, these researchers compared toneburst ABR wave V absolute latencies to the latencies of normal subjects at 1000, 2000, and 4000 Hz. In one patient with otosclerosis and a 15 dB conductive loss, these researchers measured wave V absolute latencies in response to a 1000 Hz toneburst. Specifically, these researchers measured wave V latencies of 9.65 ms, 8.75 ms, and 7.80 ms at stimulus intensities of 45, 55, and 65 dB HL, respectively. Pure-tone audiogram and specific wave V latencies for this patient can be seen below in figure 8. Overall, the results from all of the conductive patients showed increased ABR latencies due to reduction in the signal level arriving at the cochlea. However, McGee and Clemis reported that this elongation in ABR latency is different for patients with occlusion of external auditory canal or middle ear effusion versus patients with ossicular chain disorders. For patients with occlusions or middle ear effusion, the shift in wave V latency correlated well with the magnitude of the air-bone gap. In contrast, for patients with ossicular chain disorders, the increase in wave V latency was larger than expected based on the degree of the air-bone gap. These researchers believe that this larger increase in wave V latency values for individuals with ossicular chain disorders was due to mechanical artifact while recording bone conduction thresholds (McGee & Clemis, 1982).

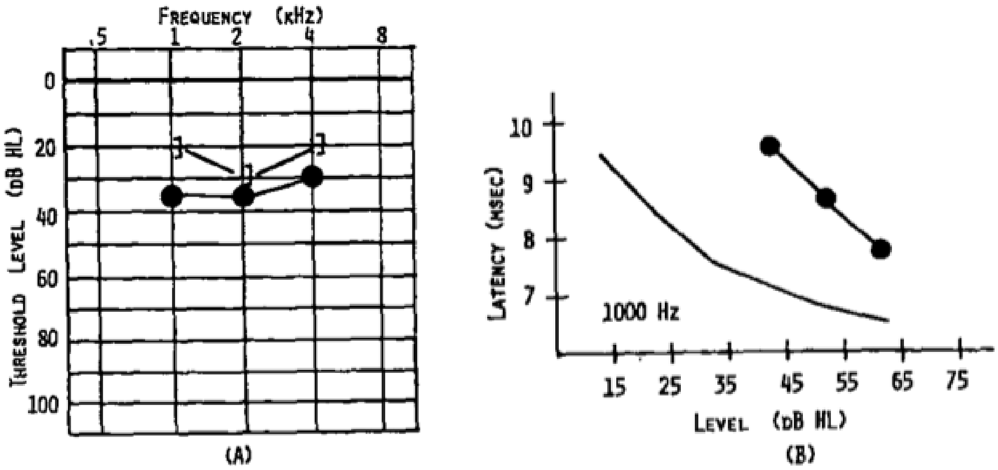

Figure 8. (A) Audiometric thresholds and (B) ABR wave V latencies for a man with otosclerosis. Air-bone gap at 1000 Hz was 15 dB (McGee & Clemis, 1982).

In order to further understand the relationship between conductive hearing loss and the auditory brainstem response, van der Drift and colleagues investigated using the ABR to distinguish between conductive and cochlear hearing loss (van der Drift, Brocaar, & Zanten, 1988). ABR thresholds and wave V absolute latencies were measured in 22 participants with normal hearing, 40 participants with conductive hearing loss, and 79 patients with cochlear hearing loss. The conductive hearing loss group consisted of 23 male and 17 female participants varying in age from 10 to 45 years. Participants' hearing loss was considered 'purely conductive' if the mean bone-conduction thresholds at all frequencies did not exceed 10 dB HL and the minimum average air-bone gap at 0.5-4 kHz was 15 dB. Participants with conductive hearing loss had a wide range of middle-ear pathologies including otitis media, perforation of eardrum, cholesteatoma, and radical mastoidectomy. van der Drift and colleagues plotted separate intensity/latency curves for all three subject groups. Results showed that for conductive hearing loss participants, the intensity/latency curve showed a strong horizontal shift to the right of the normal hearing group. The overall shape of the curve however, remained similar to the results for the normal hearing participants. The specific intensity/latency curves for conductive hearing loss and normal hearing can be seen in Figure 9 below. Based on these findings, van der Drift and colleagues concluded that conductive hearing loss causes wave V latency to increase due to the weakened signal arriving at the cochlea. However, these researchers noted that when ABR thresholds are above 30 dB nHL, it is important to use both ABR thresholds and the horizontal shift in the intensity/latency curve to more accurately distinguish between cochlear and conductive hearing loss (van der Drift, Brocaar, & Zanten, 1988).

Following van der Drift and colleagues, Ferguson et al. (1998) conducted a study to determine whether chronic conductive hearing loss in adults results in changes in the ABR similar to those observed in children with otitis media. Ferguson and colleagues recorded click-evoked ABRs in 21 normal hearing adults and 12 adults with conductive hearing impairment. Representative ABR waveforms for one participant in each patient group (normal hearing and conductive hearing loss) can be observed in figure 10. The experimental group consisted of patients with various conductive hearing loss etiologies including otosclerosis, cholesteatoma, tympanic membrane perforation, and chronic infection (Ferguson et al., 1998). These researchers calculated absolute latencies of waves I, III, and V as well as interpeak latencies between waves I-III, III-V, and I-V for each participant. Mean absolute and interpeak latencies were then compared between control and experimental groups. When compared to normal hearing individuals, Ferguson and

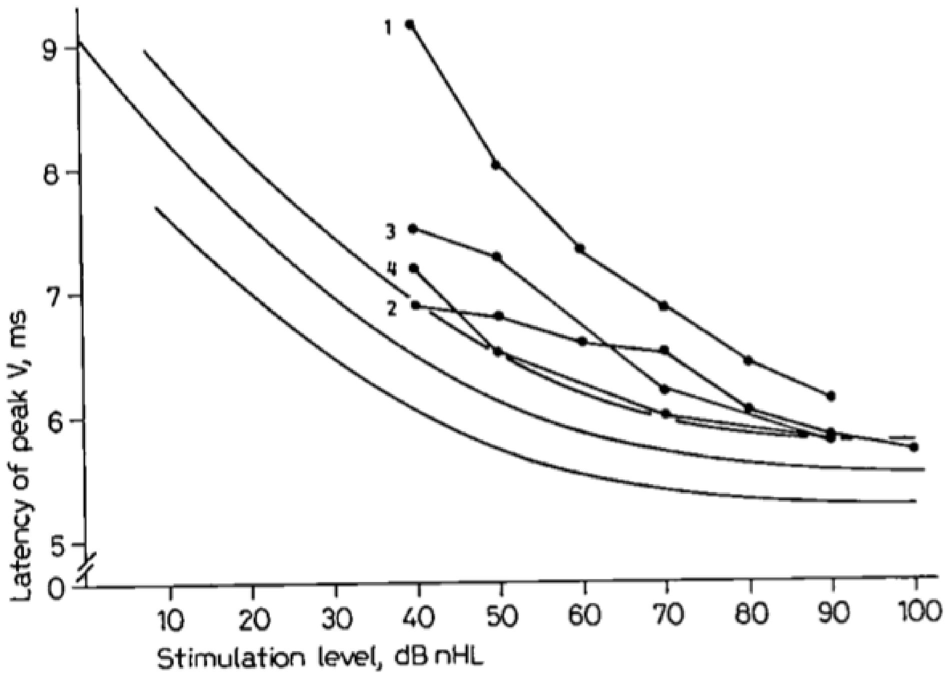

Figure 9. Reference I(L) curve with a brainstem response threshold of 40 dB nHL. Curve 1 and 2: conductive hearing losses. Curves 3 and 4: cochlear hearing losses. Unmarked curves: normal hearing. (van der Drift, Brocaar, & Zanten, 1988).

colleagues found significant delays for wave V as well as for the I-V and III-V interpeak latencies in patients with conductive hearing loss. These researchers attributed the various delays in ABR latencies to the decreased level of stimulation reaching the cochlea. Overall, Ferguson et al. (1998) found that chronic conductive hearing impairment in adults causes changes in the ABR similar to those observed in children with otitis media.

However, further research is needed in order to determine the precise cause of the abnormalities in the ABR (Ferguson et al., 1998).

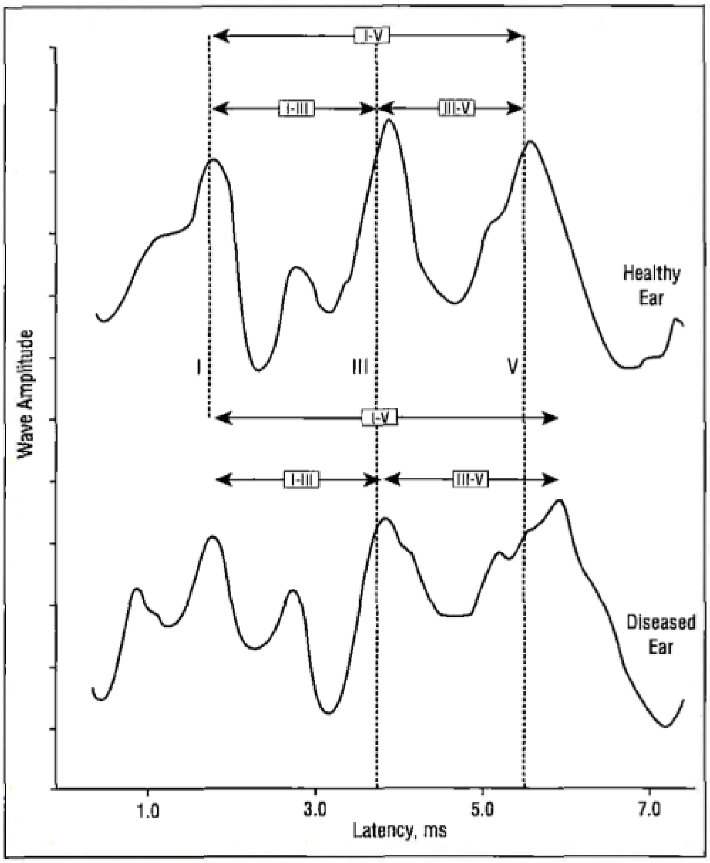

Figure 10. Representative ABR waveforms for the healthy (normal hearing) and diseased (conductive hearing loss) ears of a participant in the patient group. Patient chosen had absolute wave and interpeak latencies close to the means for each patient group (Ferguson et al., 1998).

Collectively, the results from these studies showed increased ABR absolute latencies for waves I, III, and V as a result of conductive hearing impairments. The various researchers concluded that the elongation in absolute latency values across waves occurred in response to a weakened signal arriving at the cochlea. However, these studies revealed inconsistent effects on the interpeak latencies. While some sources found interpeak latencies to remain within normal limits in conductive hearing loss participants, other studies reported significant delays in the I-V and III-V interpeak latencies (Hood, 1998; Ferguson et al., 1998). In order to better understand the effects of conductive hearing loss on the ABR recording in adults, conductive hearing loss will be simulated in normal hearing participants. The ABR measurements from the simulated conductive hearing loss group will be compared to the responses obtained from an age-matched normal hearing group. The data collected in the proposed study will then be used to create data files for the Intelligent Hearing Systems (IHS) Baby Isao Simulator. The use of simulation in different professions and audiology as well as the IHS Baby Isao Simulator will be discussed in detail in the next section of this literature review.

Simulation

Today, simulation is used in various professions for education and training. Although simulation in the areas of medicine and nursing dates back for centuries, the aviation industry was the first to use simulation for pilot training (Aebersold & Tschannen, 2013). They were able to create flight simulators that gave pilots the chance to practice flying in a safe and controlled environment. Similarly, the military and the nuclear power industry have incorporated disaster training and war games into their training programs (Aebersold & Tschannen, 2013). In the 1960s, ‘Resusci Anne’ emerged as the first medical simulator (Brown, 2017). ‘Resusci Anne’ was designed for healthcare professionals to practice on before seeing critically ill patients (Brown, 2017). Over the past five decades, simulation in the area of medicine and nursing has become a crucial part of the education of students and practicing healthcare providers (Aebersold &

Tschannen, 2013). Currently in hospitals and universities, nursing simulators allow individuals to practice with a wide range of scenarios including respiratory arrest, asthma, post-partum hemorrhage, and acute changes in mental status (Nagle, McHale, Alexander, & French, 2009).

The use of simulation as part of clinical training for healthcare professionals is common place in universities and hospitals because it allows students to practice and make mistakes in a safe and controlled environment (Barrows, 1993; Ziv et al., 2003). Students can use a simulator to practice different scenarios as many times as they would like without any concern for patient comfort or risk (Barrows, 1993; Ziv et al., 2003). Additionally, simulation exposes students to populations or disorders that would not be readily accessible in their training programs. Finally, students can use simulation to judge their own clinical skills through self-assessment. Students can practice their skills and monitor their own improvement until they are ready to work with real patients. While simulation has become a routine training exercise in many universities and hospitals, to date many audiology training programs only incorporate minimal simulation techniques.

Simulation in Audiology

There are two main types of simulation that can be used in auditory training: standardized patients and simulation technology. Standardized patients (SPs) are actors who are trained to simulate a patient's condition or disorder in a realistic manner (Barrows, 1993). Standardized patients, or simulated patients, are trained individuals that are most often used for nursing and medical students. The interaction between the SP and the student allows the student to practice their clinical and communication skills (Gilmartin et al., 2010). The use of a SP can improve a student's counseling skills, such as taking a thorough case history and breaking bad news to the patient (Gilmartin et al., 2010). In contrast, simulation technology gives the student a chance to practice his or her clinical skills with a computer program or “life-like” model. Simulation technology is often categorized in terms of their fidelity, from low to high (Aebersold & Tschannen, 2013). Several types of audiology simulation technologies currently being used at Pacific University will be discussed below.

Low fidelity simulators are non-computerized models (Brown, 2017). In audiology, an example of a low fidelity simulator is a manikin head which can be used to practice Ear Mold Impressions (EMI) and cerumen management. This type of model gives students a chance to practice and self-assess their skills before moving onto “real” patients. Mid-fidelity simulators consist of computer programs or video games. An example of a mid-fidelity simulator is The OtoSim otoscopy trainer. This trainer is a computer-based program including an artificial ear and otoscope (Brown, 2017). The OtoSim otoscopy trainer allows students to practice with hundreds of pictures of tympanic membrane pathologies (Brown, 2017). Students can then apply this knowledge when performing otoscopy on real patients. Lastly, high-fidelity stimulators use computerized manikins or models (Brown, 2017). Currently, there is only one high-fidelity simulator available in audiology, the Intelligent Hearing Systems (IHS) Baby ISAO simulator. This computerized baby manikin gives students the opportunity to practice ABR and otoacoustic emissions (OAE) testing with any manufacturer’s diagnostic system (Brown, 2017). Since the IHS Baby Isao simulator is the primary focus of this study, it will be discussed in detail below.

Intelligent Hearing Systems (IHS) Baby Isao Simulator

The IHS Baby Isao simulator was designed to simulate the generation of auditory evoked potentials and otoacoustic emissions responses (IHS Simulator User Manual, 2015). The IHS Simulator was intended for use as a teaching aid and a training tool for biomedical equipment users and students. The IHS Simulator is compatible with any brand of Evoked Potential or Otoacoustic Emissions acquisition systems (IHS Simulator User Manual, 2015). Some of the unique features of the IHS Simulator system include simulating distortion product and transient-evoked otoacoustic emissions, simulation specific hearing loss conditions and threshold profiles, and simulating poor impedances in one or more electrode positions. With the simulator, students can practice acquiring neurodiagnostic and threshold estimation evoked potentials. Additionally, they can practice skills such as measuring latencies, picking peaks, and determining degree of loss (Brown, 2017).

The IHS Baby Isao has four stainless-steel snap electrode positions. These include non-inverting forehead, inverting nape used for midline montage, non-inverting left and right mastoids for two channel set up, and back (shoulder) for the ground electrode (IHS Simulator User Manual, 2015). Additionally, three types of sound couplers can be used on Baby Isao: insert earphones, circum-aural couplers, and supra-aural couplers. An OAE probe can be placed in the ear canal using a small silicon top as well. In addition to the external components of the Baby Isao, the simulator contains internal profiles and libraries.

Profiles and Libraries

The Baby Isao simulator is programmed with various profile cases and AEP libraries. Profiles contain the definition of how the simulator will behave in response to an auditory stimulus (IHS Simulator User Manual, 2015). These definitions include threshold level at different frequencies, EEG conditions, definition of OAE recording to be used for output, and definition of AEP response library to use. Existing profiles can be edited within the IHS software. In contrast, AEP libraries are look-up tables. Depending on the definitions contained in these libraries, the simulator software will make a decision as to which waveform to output based on the detected stimulus (IHS Simulator User Manual, 2015). Libraries are helpful when trying to simulate certain types of hearing loss, such as sensorineural hearing loss. During the simulation process, the software will automatically match the detected stimulus to one of the rows in the library table and based on that information will output a “best-fitting” waveform. The “best-fitting” waveform is defined by specific parameters in the table. These parameters include type, ear, level, frequency, rate, polarity, and ipsi- and contra-response. Ultimately, the normal hearing and simulated conductive hearing loss data collected in the proposed study will be used to create new AEP libraries in the IHS Baby Isao simulator.

Statement of Purpose

The purpose of this current study is to obtain click-evoked ABR data in order to create new AEP Libraries in the Intelligent Hearing System (IHS) Baby Isao Simulator as well as to provide actual ABR data which can be used to model the effects of different degrees of conductive hearing loss on the response properties of the ABR. The click-evoked ABR data will be collected on our Intelligent Hearing System Smart Evoked

Potential System. Two groups of subjects will participate in this proposed study. One group will consist of young normal hearing adults. The second group will consist of young normal hearing adults in which a conductive hearing loss has been simulated via the use of moleskin in the tubing of the insert earphone receiver. It is expected that the range of conductive hearing loss created by the moleskin will vary from approximately 15 to 40 dB. The age range for participants in both groups will range from 18 to 25 years. Adults with normal hearing and simulated conductive hearing loss will participate in this study to accurately reflect both a normal functioning auditory system and an auditory system with conductive hearing impairment and control for effects of aging. The proposed study will specifically focus in on the following response measurements of the ABR; absolute latency of waves I, III, and V; interpeak latency (IPL) values for waves I-III, III-V, and I-V; amplitude of wave V-V' and wave I-I'; and wave V/I amplitude ratio.

Chapter 3

Materials and Methods

Subjects

Twenty-eight normal hearing participants between the ages of 18-25 years participated in the study. These participants were divided at random into two groups which were the normal-hearing control subjects and the group with simulated hearing loss. A similar number of male and female participants were recruited for each group (6 males and 8 females). Criteria for inclusion in the study were: (1) pure tone hearing thresholds that are ≤15 dB HL between 250-8000 Hz bilaterally, (2) normal middle ear function in each ear defined by middle ear pressure ranging from +50 to -150 daPa and static compliance values ranging from 0.2-1.6 ml (Shank & Shohet, 2009), and (3) present contralateral acoustic reflexes within the 90^{th} percentile at 500 Hz, 1000 Hz and 2000 Hz in each ear (Gelfand, Schwander, & Silman, 1990).

Procedures

All testing took place at Towson University in a double-walled sound treated booth made by Industrial Acoustics Company. Testing took place in one session lasting approximately sixty to ninety minutes. This test session included behavioral audiometry followed by click-evoked ABR testing. First, acoustic immittance testing using the GSI TympStar was conducted to determine if the participants met the criteria stated above for normal middle ear function. Next, behavioral air-conduction and bone-conduction thresholds were measured for 250-8000 Hz bilaterally. If both of these inclusion criteria were met, the participant moved onto click-evoked ABR testing bilaterally. The pure-tone behavioral test protocol and ABR test protocol are discussed below.

Pure-Tone Behavioral Test Protocol

All behavioral air-conduction and bone-conduction testing were completed using a GSI Audiostar audiometer. Air conduction thresholds were obtained according to the modified Hughson-Westlake procedure using pulsed pure-tone stimuli in one-octave intervals between 250-8000 Hz. Bone conduction thresholds were obtained at 500, 1000, 2000, and 4000 Hz. According to ANSI S3.21-2204 standards, participants were instructed to: "(1) Indicate the purpose of the test that, to find the faintest tone that can be heard. (2) Indicate the need to respond whenever the tone is heard, no matter how faint it may be. (3) Indicate the need to respond overtly as soon as the tone comes on and to respond immediately when the tone goes off. (4) Indicate that each ear is to be tested separately" (p. 4). Testing was completed using ER-3A insert earphones.

ABR Test Protocol

ABR Testing was completed on the Intelligent Hearing System (IHS) SmartEP system. Participants were instructed to relax or sleep within the double-walled booth. Standard EEG disc electrodes were attached to the following locations on the scalp; Fpz (ground), Cz (non-inverting), A1 and A2 (inverting for ipsilateral and contralateral ear). The areas were prepped using an alcohol wipe and a Nuprep skin prep gel to effectively reduce inter-electrode impedance values and were held in place using Ten 20 conductive paste. Impedance values at each electrode site remained less than 5000 Ohms with an inter-impedance values less than 2000 Ohms. These impedance values were monitored throughout testing to ensure consistent values. Ipsilateral and contralateral recording channels were employed.

A click stimulus, 100 μs in duration, was delivered via ER3A insert earphones. The polarity of the click stimulus was alternating and it was delivered at a rate of 19.1/sec. Stimulus intensity began at 80 dB nHL and then was decreased in 10 dB increments until threshold was determined. At least two replications of 1,024 trials were obtained at all stimulus intensities. Specific protocols for the normal hearing group and simulated conductive hearing loss group are described in detail below. Both of the subject's ears were tested with the same protocol.

An analog bandpass EEG filter of 30-3000 Hz, with a 12 dB/octave slope was employed. The ABR was recorded with a post-stimulus window of 0-12.8 ms and an artifact rejection rate of +/- 25 mV. Additionally, the ABR was recorded with the notch filter on.

The test protocol for the two subject groups is outlined below.

Normal Hearing Group

1. Acoustic immittance testing including tympanometry and acoustic reflex testing was conducted.
2. Pure-tone behavioral audiometry (air-conduction and bone-conduction) was performed.
3. Click-evoked ABRs was recorded beginning at 80 dB nHL. Stimulus intensity was decreased in 10 dB increments until a stimulus intensity of 30 dB nHL was reached. For each stimulus intensity from 80 dB nHL to 30 dB nHL, at least two replications of 1,024 trials were obtained. At stimulus intensities less than 30 dB nHL, stimulus intensity was decreased in 5 dB increments until the participant's ABR threshold was

determined. For each stimulus intensity less than or equal to 30 dB nHL, at least three replications of 1,024 trials were obtained.

Simulated Conductive Hearing Loss Group

1. Acoustic immittance testing including tympanometry and acoustic reflex testing was conducted.
2. Baseline pure-tone behavioral audiometry prior to simulating the conductive hearing loss was performed.
3. The conductive hearing loss was simulated by placing 5 mm moleskin in the ER3A insert earphone tubing. This simulation was created in each ear. The pure-tone audiogram from 250-8000 Hz was repeated to determine the magnitude of the conductive impairment that was created. The range of conductive hearing loss was approximately 20 to 45 dB across subjects.
4. Click-evoked ABRs was recorded beginning at 80 dB nHL. Stimulus intensity was decreased in 10 dB increments until 60 dB nHL was reached. For each stimulus intensity from 80 dB nHL to 60 dB nHL, at least two replications of 1,024 trials were obtained. Below 60 dB nHL, the stimulus intensity was decreased in 5 dB increments until the participant’s ABR threshold was determined. For each stimulus intensity less than 60 dB nHL, at least three replications of 1,024 trials were obtained.

Calibration

The IHS SmartEP system was calibrated for intensity, linearity, and stimulus polarity by Kimmetrics prior to any data collection. All calibration data collected for intensity and linearity checks were within normal limits according to manufacturer specifications. Additionally, a reversal in stimulus polarity was recorded for the rarefaction versus condensation click stimuli during calibration. A copy of the "Certificate of Calibration" as well as relevant documentation from calibration can be seen in Appendix A **(**pages 106-108).

Response Measurements

For each test condition, a summed response was created from either the 2 or 3 replications contributing to the sum. Separate summed responses were created for the ipsilateral and contralateral recordings. The following response measures were taken on the summed ipsilateral responses: (1) absolute latencies of waves I, III, and V (2) interpeak latencies of I-III, III-V, and I-V (3) peak-to-peak amplitudes of wave V-V' and wave I-I' and (4) wave V/I amplitude ratio. The absolute latency of waves I and III were taken on the peak of each of these waves. The absolute latency of wave V was taken on the shoulder of wave V unless a clear separation of wave IV and wave V was seen in the contralateral tracing.

Statistical Analysis

Descriptive statistics (mean and standard deviation) were calculated separately for subject group. These statistics were calculated separately for each latency and amplitude measurement described above and for the V/I amplitude ratios at each stimulus intensity. Interaural wave V and I-V interpeak values were also calculated for each test condition. A series of independent t-tests were conducted to determine if there were any significant difference in any of the response measures between right and left ears. These t-tests were run separately for each response measurement at each stimulus intensity. An alpha level of $p < 0.05$ was originally employed to determine statistical significance. However, since multiple t-tests were completed, there was an increase in the chance of type I error. To correct for this, a Bonferroni correction factor was calculated by diving the original *p*-value (0.05) by the number of t-tests completed (61). This resulted in a corrected alpha level of $p < 0.001$ which was then used to determine statistical significance between ears. If no significant differences were found in these ABR response measures, then data across ears was combined for those test conditions.

Chapter 4

Results

In this study, pure tone behavioral audiometry, acoustic immittance testing, and click-evoked ABR testing were performed on 28 participants. Participants were divided at random into two groups of 14 participants each; the normal-hearing control subjects and the group with simulated conductive hearing loss. The ABR was recorded to click stimuli in both the right and left ears of each subject. The stimulus intensity began at a high intensity, 80 dBnHL, and was decreased in 5-10 dB increments until the ABR threshold was determined.

The ABR's from each participant were analyzed in terms of five characteristics of the response. These characteristics include: the absolute latency measurements of waves I, III, and V; the interpeak latencies of waves I-III, III-V, and I-V; the interaural latency differences of IT5 and I-V; the peak-to-peak amplitude values of waves I-I' and V-V'; and the V/I amplitude ratio.

A series of 61 t-tests were run to determine if there was any significant difference in the ABR latency and amplitude measurements between ears. Each latency and amplitude measurement for each ABR wave was analyzed separately at each stimulus intensity. The results of these series of t-test revealed *p*-values ranging from 0.06 to 1.00, indicating no significant differences between ears for any of the latency and amplitude values. Therefore, the data was collapsed across ears for all latency and amplitude response measurements. Ear specific results for the various latency and amplitude measurements for each participant can be found in Appendix C through J **(**normal hearing group: pages 111-122; conductive hearing loss group; pages 123-133).

In this results section, the normal participants' data will be presented first, followed by the data from the simulated conductive hearing loss group. Within these two sections, the results of the pure tone behavioral testing will be presented first, followed by the acoustic immittance and ABR results. The various ABR latency results will precede a discussion of the ABR amplitude findings. Lastly, a third section of the results will compare the ABR findings from these two subject groups. This same organization strategy will be employed in the discussion section.

Normal Hearing Group

In this study, baseline behavioral pure tone audiometry, acoustic immittance testing, and ABR testing were performed on 14 normal hearing participants. The results of this testing will be discussed separately in the sub-sections below.

Behavioral Pure Tone Testing

All 14 participants met the criteria for normal hearing including pure tone air conduction thresholds that are ≤15 dB HL between 250-8000 Hz, bilaterally. Pure tone air conduction thresholds ranged from -5 dB to 15 dB HL across subjects. No air/bone gaps were recorded. The mean air conduction thresholds ranged from 2.5 to 7.5 dB HL across frequencies. There was no observable difference in thresholds between the ears. The variability in threshold data, reflected in the SD values, was small and consistent across frequencies. For all 14 normal hearing participants, specific pure-tone air conduction thresholds from 250-8000 Hz for right and left ears as well as mean thresholds and associated SD values are shown in table 2.

Acoustic Immittance Testing

All 14 participants had type A tympanograms and met the criteria for normal middle ear function in each ear defined by middle ear pressure ranging from +50 to -150 daPa and static compliance values ranging from 0.2-1.6 ml (Shank & Shohet, 2009). Similarly, all 14 participants had present contralateral acoustic reflexes which occurred within the 90th percentile at 500 Hz, 1000 Hz and 2000 Hz in each ear (Gelfand, Schwander, & Silman, 1990). The mean values and the range of values obtained for middle ear pressure, static compliance, and acoustic reflex thresholds are shown in table 3.

Auditory Brainstem Response Testing

For all 14 normal hearing participants, the ABR was recorded in both right and left ears to click stimuli beginning at 80 dBnHL. As previously stated, stimulus intensity was decreased in 10 dB increments until a stimulus intensity of 30 dBnHL was reached. At stimulus intensities less than 30 dB nHL, stimulus intensity was decreased in 5 dB increments until the participant's ABR threshold was determined. ABR latency and amplitude measurements were taken on each participant's data at each stimulus intensity. Each of these latency and amplitude results will be discussed below.

Absolute latency values of waves I, III, and V

As expected, the mean latency values of waves I, III, and V increased as stimulus intensity decreased from 80 dBnHL to threshold. These mean latency values and associated SD values are shown in table 4. This table also contains the number of ears who were judged to have replicable responses at those stimulus intensities. The

Table 2

Individual Participants' Pure Tone Air Conduction Thresholds, Mean, and Standard Deviation Values for NH Group

		Frequency (Hz)					
Participant	**Ear**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
1	A_D	5	5	5	0	0	-5
	A_S	5	5	5	5	-5	-5
2	A_D	5	5	10	10	5	10
	A_S	5	5	5	5	10	5
3	A_D	0	5	0	10	10	5
	A_S	5	5	0	10	10	10
4	A_D	0	5	0	5	5	-5
	A_S	5	10	5	5	10	-5
5	A_D	10	10	10	0	0	5
	A_S	10	5	10	0	5	10
6	A_D	10	5	0	5	10	0
	A_S	5	0	0	0	5	0
7	A_D	5	0	5	0	0	-5
	A_S	5	10	10	5	0	5
8	A_D	5	0	5	5	0	10
	A_S	5	5	0	5	15	10
9	A_D	10	15	15	15	10	0
	A_S	15	15	15	15	15	0
10	A_D	15	10	15	10	10	10
	A_S	10	10	10	10	5	10
11	A_D	10	5	10	5	0	0
	A_S	10	5	10	5	0	0
12	A_D	5	0	5	0	0	-5
	A_S	5	5	0	0	0	0
13	A_D	15	10	15	10	10	10
	A_S	15	10	10	10	10	10
14	A_D	5	5	0	0	5	5
	A_S	5	5	5	0	5	10
A_D	**Mean**	**7.14**	**5.71**	**6.79**	**5.36**	**4.64**	**2.5**
	SD	(4.69)	(4.32)	(4.32)	(4.99)	(4.58)	(6.12)
A_S	**Mean**	**7.50**	**6.79**	**6.07**	**5.36**	**6.07**	**4.29**
	SD	(3.80)	(3.72)	(3.72)	(4.58)	(5.94)	(5.84)

Table 3.

Mean and Range Values for Immittance Testing of Normal Hearing Group (n=14)

Ear		Tympanometry		Acoustic Reflex Thresholds		
		Middle Ear Pressure (daPa)	Static Compliance (mL)	500 Hz	1000 Hz	2000 Hz
A_D	**Mean**	**-9.29**	**0.82**	**92.5**	**92.5**	**92.1**
	Range	(-100-25)	(0.5-1.9)	(80-100)	(80-100)	(85-100)
A_S	**Mean**	**3.00**	**0.78**	**90.4**	**91.1**	**90.7**
	Range	(-40-40)	(0.4-1.7)	(85-100)	(85-100)	(85-100)

variability in these absolute latency values, reflected in the SD measures, was small, ranging between 0.10-0.79 across all waves.

As expected, the early components of the ABR, waves I and III, disappeared at stimulus intensities of 50 dBnHL and 40 dBnHL, respectively. Similarly, the number of ears with identifiable and replicable waves I and III decreased from 80 dBnHL to the intensities at which the waves disappeared. Specifically, wave I was recorded in 28 ears at 80 dBnHL, 12 ears at 60 dBnHL, and 0 ears at 50 dBnHL. Wave III was present in 28 ears at 80 dBnHL, 16 ears at 50 dBnHL, and 0 ears at 40 dBnHL.

In contrast, wave V was consistently present in all 28 ears down to a low stimulus intensity, 20 dBnHL. At 15 dBnHL, wave V was recorded in the majority of ears (n=26). The lowest stimulus intensity in which wave V was recorded was 5 dBnHL and it was present in 6 ears at this lowest stimulus intensity.

As expected, the largest shift in absolute latency as a function of stimulus intensity occurred for wave V. Specifically, as stimulus intensity was decreased from 80 dBnHL to 60 dBnHL, there was a 0.47 ms increase in wave V. This was followed by a 0.33 ms shift of wave I and a 0.29 ms shift of wave III.

Interpeak latency values of I-III, III-V, and I-V

In all 14 normal hearing participants, interpeak latencies were measured for waves I-III, III-V, and I-V. The descriptive statistics (mean and standard deviation) for the various interpeak latency values for clicks presented at intensities ranging from 50-80 dBnHL are displayed in table 5 below. As expected, there were essentially no changes in any of the mean interpeak latency values as a function of stimulus intensity. Specifically, the interpeak latency values for waves I-III ranged from 2.18 to 2.24 ms at these stimulus intensities. Similarly, the interpeak latency of waves III-V ranged from 1.76-1.80 ms. Lastly, the interpeak latency of waves I-V ranged from 4.01 to 4.03 ms. The variability in all three interpeak latency measurements, reflected in the SD measures, was small, ranging from 0.09 to 0.24.

Interaural latency differences

The interaural latency differences were calculated for the absolute latency of wave V and for the I-V interpeak latency at each stimulus intensity. The mean interaural latency difference values and associated SD values for each stimulus intensity are shown in table 6. The mean interaural difference values for wave V increased as a function of stimulus intensity. The mean interaural difference values for wave V ranged from 0.09 ms to 0.44 ms, at 80 dBnHL and 5 dBnHL, respectively. The variability in wave V interaural latency differences, shown by SD values, ranged from 0.09 to 0.49. It should be noted that variability increased as a function of stimulus intensity. Specifically, variability was relatively small (0.09-0.14) at moderate to high stimulus intensities (30-80 dBnHL) and then increased substantially at low stimulus intensities (≤ 25 dBnHL).

Table 4

Mean and Standard Deviation Values for the Absolute Latency of Waves I, III, and V in ms for Normal Hearing Participants

Stimulus Intensity		Absolute Latency (ms)		
		Wave I	**Wave III**	**Wave V**
80 dBnHL	**Mean**	**1.70**	**3.94**	**5.73**
	SD	(0.10)	(0.20)	(0.21)
	N	28	28	28
70 dBnHL	**Mean**	**1.86**	**4.08**	**5.94**
	SD	(0.12)	(0.19)	(0.24)
	N	25	24	28
60 dBnHL	**Mean**	**2.03**	**4.23**	**6.20**
	SD	(0.13)	(0.29)	(0.30)
	N	12	16	28
50 dBnHL	**Mean**		**4.47**	**6.53**
	SD		(0.18)	(0.32)
	N		5	28
40 dBnHL	**Mean**			**7.03**
	SD			(0.47)
	N			28
30 dBnHL	**Mean**			**7.54**
	SD			(0.58)
	N			28
25 dBnHL	**Mean**			**7.93**
	SD			(0.69)
	N			28
20 dBnHL	**Mean**			**8.32**
	SD			(0.76)
	N			28
15 dBnHL	**Mean**			**8.74**
	SD			(0.79)
	N			26
10 dBnHL	**Mean**			**8.85**
	SD			(0.61)
	N			17
5 dBnHL	**Mean**			**9.09**
	SD			(0.36)
	N			6

Table 5

Descriptive Statistic Values (Mean and Standard Deviation) and Number of Ears (N) for the Interpeak Latencies of Waves I-III, III-V, and I-V to Click-Evoked ABRs

		Interpeak Latency (ms)		
Stimulus Intensity		I-III	III-V	I-V
80 dBnHL	**Mean**	**2.24**	**1.80**	**4.03**
	SD	(0.15)	(0.16)	(0.19)
	N	28	28	28
70 dBnHL	**Mean**	**2.23**	**1.83**	**4.06**
	SD	(0.16)	(0.14)	(0.22)
	N	24	24	24
60 dBnHL	**Mean**	**2.18**	**1.86**	**4.01**
	SD	(0.20)	(0.24)	(0.24)
	N	12	16	12
50 dBnHL	**Mean**		**1.76**	
	SD		(0.09)	
	N		5	

Similarly, the mean interaural difference values for the I-V interpeak latency increased as a function of stimulus intensity. The mean interaural difference values for waves I-V ranged from 0.12 ms to 0.19 ms, at 80 dBnHL and 60 dBnHL, respectively. Interaural difference values for waves I-V could not be calculated below 60 dBnHL because identifiable and replicable wave I responses were not obtained. The variability in I-V interpeak latency values, represented by SD values, was small, ranging from 0.10 to 0.12.

In adults with normal hearing and normal oto-neurologic function, the maximum acceptable interaural difference for wave V absolute latency and I-V interpeak latency ranges from 0.2 to 0.4 ms (Bauch, Olsen & Pool, 1996; Don & Kwong, 2009). In the current study, the mean interaural latency differences for wave V met this criterion down to and including 10 dBnHL. Similarly, the mean interaural latency differences for I-V interpeak latency were within normal limits, ranging from 0.12 to 0.19 ms. It should be noted that mean interaural latency differences for wave V could only be calculated at high intensities, 60 dBnHL to 80 dBnHL.

Amplitude values

The peak-to-peak amplitude measurements of waves I-I’ and V-V’ were taken on both ears of all 14 normal hearing participants. The data from both of these measurements were used to calculate the wave V/I amplitude ratios for each ear. As expected, the mean amplitudes of waves I-I’ and V-V’ showed a decrease as stimulus intensity decreased, as seen in table 7. The variability in amplitude measurement for wave I-I’, as seen in SD values, ranged from 0.07 to 0.13. Similarly, the variability in amplitude measurement for wave V-V’ ranged from 0.10 to 0.30. These SD values are similar to those measured for the absolute latency measurements.

Specifically, the peak-to-peak amplitudes of wave I-I’ decreased from 0.36 μV at 80 dBnHL to 0.15 μV at 60 dBnHL. At stimulus intensities below 60 dBnHL, a replicable wave I was not present. In contrast, the peak-to-peak amplitude of wave V-V’ was recorded down to 5 dBnHL. Wave V-V’ peak-to-peak amplitude values decreased from 0.69 μV at 80 dBnHL to 0.13 μV at 5 dBnHL. It should be noted that the mean wave V-V’ peak-to-peak amplitude at 80 dBnHL was based on responses from 28 ears, whereas the mean V-V’ amplitude value at 5 dBnHL was only based on 6 ears. Wave V peak-to-peak amplitude was consistent in 28 ears down to 20 dBnHL. The mean wave V/I amplitude ratios ranged from 2.09 μV at 80 dBnHL to 4.44 μV at 60 dBnHL.

Table 6

Mean and Standard Deviation for Interaural Latency Differences of Wave V and I-V Interpeak Latency

		Interaural Latency Difference (ms)	
Stimulus Intensity		**Wave V**	**I-V**
80 dBnHL	**Mean**	**0.09**	**0.12**
	SD	(0.11)	(0.10)
	N	14	14
70 dBnHL	**Mean**	**0.13**	**0.12**
	SD	(0.09)	(0.11)
	N	14	12
60 dBnHL	**Mean**	**0.13**	**0.19**
	SD	(0.11)	(0.12)
	N	14	2
50 dBnHL	**Mean**	**0.14**	
	SD	(0.10)	
	N	14	
40 dBnHL	**Mean**	**0.19**	
	SD	(0.14)	
	N	14	
30 dBnHL	**Mean**	**0.23**	
	SD	(0.20)	
	N	14	
25 dBnHL	**Mean**	**0.20**	
	SD	(0.22)	
	N	14	
20 dBnHL	**Mean**	**0.27**	
	SD	(0.23)	
	N	14	
15 dBnHL	**Mean**	**0.33**	
	SD	(0.24)	
	N	12	
10 dBnHL	**Mean**	**0.37**	
	SD	(0.49)	
	N	5	
5 dBnHL	**Mean**	**0.44**	
	SD	(0.47)	
	N	2	

In normal hearing adults with intact peripheral and central auditory pathways, V/I amplitude ratios should be greater than or equal to 0.5 μV (Hall, 2007). In this study, the mean wave V/I amplitude ratios were well above this 0.5 μV criteria at all stimulus intensities where a V/I amplitude ratio could be calculated. The variability for the wave V/I amplitude ratio increased with decreasing intensity from 0.08 to 1.81 at 80 dBnHL and 60 dBnHL, respectively. This variability may be due to the decreased number of participants with a present wave I at 60 dBnHL.

ABR Thresholds

For all normal hearing participants, ABR threshold was determined by the lowest stimulus intensity at which an identifiable and replicable wave V was present. ABR thresholds for individual participants' as well as descriptive statistics (mean and standard deviation values) are shown in table 8. In normal hearing participants, ABR thresholds ranged from 5 to 20 dBnHL. Mean ABR thresholds for right and left ears were 10 dBnHL and 12.14 dBnHL, respectively. In 28 ears, wave V was identifiable and replicable down to 20 dBnHL. It was interesting to note that wave V was present and replicable in the majority of ears (n=26) down to 15 dBnHL. The lowest ABR threshold, 5 dBnHL, was recorded in only 6 ears total.

Table 7

Descriptive Statistic Values for Amplitude Values of Wave I-I', V-V', and V/I Ratio in NH Group

Stimulus Intensity		Peak-to-Peak Amplitude (μV)		Amplitude Ratio (μV)
		I-I'	V-V'	V/I
80 dBnHL	**Mean**	**0.36**	**0.69**	**2.09**
	SD	(0.11)	(0.17)	(0.80)
	N	28	28	28
70 dBnHL	**Mean**	**0.23**	**0.65**	**3.37**
	SD	(0.13)	(0.21)	(1.75)
	N	25	28	25
60 dBnHL	**Mean**	**0.15**	**0.58**	**4.44**
	SD	(0.07)	(0.30)	(1.81)
	N	12	28	12
50 dBnHL	**Mean**		**0.43**	
	SD		(0.13)	
	N		28	
40 dBnHL	**Mean**		**0.42**	
	SD		(0.10)	
	N		28	
30 dBnHL	**Mean**		**0.37**	
	SD		(0.12)	
	N		28	
25 dBnHL	**Mean**		**0.30**	
	SD		(0.10)	
	N		28	
20 dBnHL	**Mean**		**0.26**	
	SD		(0.08)	
	N		28	
15 dBnHL	**Mean**		**0.20**	
	SD		(0.07)	
	N		26	
10 dBnHL	**Mean**		**0.18**	
	SD		(0.06)	
	N		17	
5 dBnHL	**Mean**		**0.13**	
	SD		(0.05)	
	N		6	

Table 8

Individual ABR Thresholds as well as Mean and Standard Deviation Values for Normal Hearing Group

	ABR Threshold (dBnHL)	
Participant	**A_D**	**A_S**
1	10	10
2	15	15
3	10	15
4	5	10
5	10	10
6	10	15
7	5	5
8	10	15
9	15	20
10	15	15
11	10	10
12	5	5
13	15	10
14	5	15
Mean	**10**	**12.14**
SD	(3.92)	(4.26)

Simulated Conductive Hearing Loss Group

All the subjects in this simulated group were initially seen for a baseline audiogram which consisted of measuring pure tone air conduction thresholds from 250 to 8000 Hz in each ear. Then, 5 mm of moleskin was placed in the tubing for the ER3A insert receivers and the air conduction thresholds were re-measured in each ear. Then, acoustic immittance testing was conducted to rule out any middle ear pathology. Lastly, click-evoked ABR testing was conducted. The results of this testing will be discussed separately in the sub-sections below.

Behavioral Pure Tone Testing

All 14 participants met the criteria for baseline normal hearing including pure tone hearing thresholds that are ≤15 dB HL between 250-8000 Hz, bilaterally. Pure tone air conduction thresholds ranged from -5 dB to 15 dB HL across frequencies. This finding was true in each ear. No air/bone gaps were recorded. Once the 5 mm of moleskin was placed, air conduction thresholds were re-assessed. All of the participants had air conduction thresholds ranging from 25 to 55 dB HL. For all 14 participants, individual baseline normal hearing pure tone thresholds and simulated conductive pure tone thresholds for right and left ears are shown in table 9. This table also includes mean and standard deviation values for these thresholds.

The mean baseline thresholds ranged from 2.5 to 8.6 dB HL across frequencies in each ear. In contrast, the mean simulated conductive thresholds ranged from 32.1 to 42.9 dB HL across frequencies. The lowest mean simulated thresholds were measured at 4000 Hz, whereas the highest mean simulated threshold were measured at 250 Hz.

For each conductive hearing loss participant, a behavioral pure tone threshold shift was calculated for each frequency, 250 to 8000 Hz, in each ear. These threshold shifts for individual participants ranged from 20 to 45 dB HL as seen in table 10. Mean threshold shifts across ears ranged 27.14 to 36.43 dB HL. The magnitude of the threshold shifts was relatively similar across frequency as well as across ears.

Acoustic Immittance Testing

All 14 participants in this simulated conductive hearing loss group had type A tympanograms and met the criteria for normal middle ear function in each ear defined by middle ear pressure ranging from +50 to -150 daPa and static compliance values ranging

Table 9

Descriptive Statistics for Baseline Normal Hearing (NH) and Simulated Conductive Hearing Loss (CHL) Pure Tone Thresholds for Conductive Group

		Frequency (Hz)											
		250		500		1000		2000		4000		8000	
Participant	Ear	NH	CHL	NH	CHL	NH	CHL	NH	CHL	NH	CHL	NH	CHL
15	AD	15	45	15	50	15	45	10	40	10	45	10	40
	AS	5	40	10	40	5	35	5	35	0	35	5	40
16	AD	0	35	5	35	5	35	0	30	-5	30	-5	30
	AS	0	30	0	30	0	30	-5	25	-5	25	-5	25
17	AD	0	40	5	35	5	35	5	40	5	40	10	50
	AS	0	35	0	30	5	30	5	30	10	40	15	55
18	AD	10	45	10	40	5	35	5	35	0	40	0	45
	AS	5	45	5	35	5	30	0	35	0	30	0	30
19	AD	5	40	0	40	-5	35	5	35	10	45	10	50
	AS	5	35	5	35	5	35	10	35	10	50	10	55
20	AD	15	45	10	45	5	35	5	35	5	40	0	45
	AS	15	45	15	40	10	35	5	30	5	35	-5	30
21	AD	10	40	5	35	10	35	10	40	5	45	0	40
	AS	5	35	0	30	5	30	10	35	5	40	0	30
22	AD	5	40	0	30	5	35	5	35	0	40	15	40
	AS	10	45	0	30	5	35	5	30	10	45	15	45
23	AD	10	45	10	40	5	35	5	35	5	45	-5	35
	AS	5	40	10	35	5	35	10	30	10	45	0	35
24	AD	15	55	15	40	10	40	5	35	0	40	-5	30
	AS	15	45	10	35	10	30	5	30	10	40	0	30
25	AD	5	35	5	35	0	30	0	35	-5	35	-5	30
	AS	5	35	0	30	0	30	0	30	0	30	-5	30
26	AD	10	45	10	40	5	35	0	35	0	40	0	30
	AS	10	45	5	35	5	35	0	30	0	40	0	35
27	AD	10	45	15	45	15	45	15	45	10	50	5	40
	AS	15	50	15	40	15	45	15	40	15	45	5	40
28	AD	10	45	10	40	5	35	10	35	5	40	5	40
	AS	10	35	5	40	0	30	5	35	0	35	5	35
AD	**Mean**	**8.6**	**42.9**	**8.2**	**39.3**	**6.1**	**36.4**	**5.7**	**36.4**	**3.2**	**41.1**	**2.5**	**38.9**
	SD	(5.0)	(5.1)	(5.0)	(5.1)	(5.3)	(4.1)	(4.3)	(3.6)	(5.0)	(4.9)	(6.7)	(7.1)
AS	**Mean**	**7.5**	**40**	**5.7**	**34.6**	**5.4**	**33.2**	**5.0**	**32.1**	**5.0**	**38.2**	**2.9**	**36.8**
	SD	(5.1)	(5.9)	(5.5)	(4.1)	(4.1)	(4.2)	(5.2)	(3.8)	(5.9)	(7.0)	(6.7)	(9.3)

Table 10.

Behavioral Pure Tone Threshold Shifts for Simulated Conductive Hearing Loss Group

		Frequency (Hz)					
Participant	**Ear**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
15	A_D	30	35	30	30	35	30
	A_S	35	30	30	30	35	35
16	A_D	35	30	30	30	35	35
	A_S	30	30	30	30	30	30
17	A_D	40	30	30	35	35	40
	A_S	35	30	25	25	30	40
18	A_D	35	30	30	30	40	45
	A_S	40	30	25	35	30	30
19	A_D	35	40	40	30	35	40
	A_S	30	30	30	25	40	45
20	A_D	30	35	30	30	35	45
	A_S	30	25	25	25	30	35
21	A_D	30	30	25	30	40	40
	A_S	30	30	25	25	35	30
22	A_D	35	30	30	30	40	25
	A_S	35	30	30	25	35	30
23	A_D	35	30	30	30	40	40
	A_S	35	25	30	20	35	35
24	A_D	40	25	30	30	40	35
	A_S	30	25	20	25	30	30
25	A_D	30	30	30	35	40	35
	A_S	35	30	30	30	30	35
26	A_D	35	30	30	35	40	30
	A_S	35	30	30	30	40	35
27	A_D	35	30	30	30	40	35
	A_S	35	25	30	25	30	35
28	A_D	35	30	30	25	35	35
	A_S	25	35	30	30	35	30
A_D	**Mean**	**34.29**	**31.07**	**30.36**	**30.71**	**37.86**	**36.43**
	SD	(3.31)	(3.50)	(3.08)	(2.67)	(2.57)	(5.69)
A_S	**Mean**	**32.86**	**28.93**	**27.86**	**27.14**	**33.21**	**33.93**
	SD	(3.78)	(2.89)	(3.23)	(3.78)	(3.72)	(4.46)

from 0.2-1.6 ml (Shank & Shohet, 2009). Similarly, all 14 participants had present contralateral acoustic reflexes that occurred within the 90th percentile at 500 Hz, 1000 Hz and 2000 Hz in each ear (Gelfand, Schwander, & Silman, 1990). The mean values and

the range of values obtained for middle ear pressure, static compliance, and acoustic reflex thresholds are shown in table 11 below.

Table 11.

Mean and Range for Acoustic Immittance Testing of Simulated HL Group (n=14)

Ear		Tympanometry		Acoustic Reflex Threshold		
		Middle Ear Pressure (daPa)	**Static Compliance (mL)**	**500 Hz**	**1000 Hz**	**2000 Hz**
A_D	**Mean**	**4.64**	**0.94**	**86.8**	**88.9**	**89.6**
	Range	(-65-35)	(0.6-1.3)	(80-90)	(85-95)	(85-95)
A_S	**Mean**	**1.43**	**0.90**	**87.1**	**88.2**	**89.3**
	Range	(-10-10)	(0.5-1.4)	(80-95)	(80-95)	(80-95)

Auditory Brainstem Response Testing

For all 14 conductive hearing loss participants, the ABR was recorded using ER3A insert earphone tubing with 5 mm moleskin placed in right and left tubing. The ABR was recorded in both right and left ears to click stimuli beginning at 80 dBnHL. Stimulus intensity was decreased in 10 dB increments until a stimulus intensity of 60 dBnHL was reached. At stimulus intensities less than 60 dBnHL, stimulus intensity was decreased in 5 dB increments until the participant’s ABR threshold was determined. ABR latency and amplitude measurements were taken on each participant’s data at each stimulus intensity. Each of these latency and amplitude results will be discussed below.

Absolute latency values of waves I, III, and V

As expected, the mean latency values of waves I, III, and V increased as stimulus intensity decreased from 80 dBnHL to threshold. These mean latency values and associated SD values are shown in table 12. The variability in these absolute latency values, reflected in the SD measures, was small, across all waves especially at higher stimulus intensities. Specifically, for wave I the variability ranged from 0.20 to 0.21. For wave III, the variability ranged from 0.36 to 0.54. For wave V, the variability ranged from 0.36 to 0.83. Additionally, variability increased as stimulus intensity was decreased. As expected, the early components of the ABR, waves I and III, disappeared at a high stimulus intensity of 60 dBnHL. Similarly, the number of ears with waves I and III decreased from 80 dBnHL to 70 dBnHL. Specifically, wave I was recorded in 7 ears at 80 dBnHL, 2 ears at 70 dBnHL, and 0 ears at 60 dBnHL. Wave III was present in 11 ears at 80 dBnHL, 7 ears at 70 dBnHL, and 0 ears at 60 dBnHL.

In contrast, wave V was consistently present in all 28 ears down to and including 55 dBnHL. Wave V was present in the majority of ears, 26 ears, down to 40 dBnHL. 30 dBnHL was the lowest stimulus intensity in which wave V was recorded in a total of 9 ears.

As expected, the largest shift in latency as a function of stimulus intensity, from 80 dBnHL to 70 dBnHL, occurred for wave V which was 0.51 ms increase. This was followed by a 0.50 ms shift of wave III and finally a 0.25 ms shift of wave I.

Interpeak latency values of I-III, III-V, I-V

In all conductive hearing loss participants, interpeak latencies were measured for waves I-III, III-V, and I-V. Descriptive statistics (mean and standard deviation) for the various interpeak latency values for clicks presented at intensities ranging from 70 to 80 dBnHL are displayed in table 13. As expected, there were essentially no changes in any of the mean interpeak latency values as a function of stimulus intensity. The interpeak latency values of waves I-III ranged from 2.01 ms to 2.03 ms. Similarly, the interpeak latency of waves III-V ranged from 2.09 ms to 2.17 ms. The interpeak latency of waves I-

V ranged from 3.81 ms to 3.91 ms. All interpeak latencies could not be measured below 70 dBnHL because early components, wave I and III, disappeared at 60 dBnHL. The variability in all three interpeak latency measurements, reflected in the SD measures, was small, ranging from 0.05 to 0.76.

Interaural latency differences

The interaural latency differences were calculated for the absolute latency of wave V and for the I-V interpeak latency at each stimulus intensity. The mean interaural latency difference values and associated SD values for each stimulus intensity are shown in table 14. The mean interaural difference values fell within the expected normative range (≤ 0.4 ms) for intensities of 60 to 80 dBnHL. At the lower stimulus intensities, the mean interaural difference values for wave V increased as a function of stimulus intensity. The mean interaural difference values for wave V ranged from 0.23 ms to 1.37 ms, from 80 dBnHL to 35 dBnHL, respectively. The variability in wave V interaural latency differences, shown by SD values, increased substantially as stimulus intensity decreased below 50 dBnHL.

The mean interaural difference values for waves I-V could only be calculated for the highest stimulus intensity, 80 dBnHL. The mean interaural latency difference value for wave I-V at 80 dBnHL was 0.19 ms. It should be noted that the mean interaural difference value for wave I-V was calculated based on the data from two participants.

Interaural difference values for waves I-V could not be calculated below 80 dBnHL because identifiable and replicable wave I responses were not obtained. The variability in I-V interpeak latency values, represented by SD values, was small, measuring 0.25.

Table 12

Descriptive Statistics for Absolute Latency of Waves I, III, and V in Conductive Hearing Loss Group

Stimulus Intensity		Absolute Latency (ms)		
		Wave I	**Wave III**	**Wave V**
80 dBnHL	**Mean**	**2.18**	**4.10**	**6.46**
	SD	(0.20)	(0.36)	(0.36)
	N	7	11	28
70 dBnHL	**Mean**	**2.43**	**4.60**	**6.97**
	SD	(0.21)	(0.54)	(0.49)
	N	2	7	28
60 dBnHL	**Mean**			**7.49**
	SD			(0.55)
	N			28
55 dBnHL	**Mean**			**8.00**
	SD			(0.67)
	N			28
50 dBnHL	**Mean**			**8.30**
	SD			(0.64)
	N			27
45 dBnHL	**Mean**			**8.68**
	SD			(0.63)
	N			27
40 dBnHL	**Mean**			**9.20**
	SD			(0.71)
	N			26
35 dBnHL	**Mean**			**9.53**
	SD			(0.81)
	N			16
30 dBnHL	**Mean**			**9.70**
	SD			(0.83)
	N			9

Table 13

Descriptive Statistics for Interpeak Latencies of Waves I-III, III-V, and I-V for Conductive Hearing Loss Group

Stimulus Intensity		Interpeak Latency (ms)		
		I-III	**III-V**	**I-V**
80 dBnHL	**Mean**	**2.01**	**2.09**	**3.91**
	SD	(0.22)	(0.44)	(0.30)
	N	5	11	7
70 dBnHL	**Mean**	**2.03**	**2.17**	**3.81**
	SD	(0.25)	(0.76)	(0.05)
	N	2	7	2

Amplitude values

The peak-to-peak amplitude measurements of wave I-I' and V-V' were taken on both ears of all conductive hearing loss participants. The data from both of these measurements were used to calculate the wave V/I amplitude ratio of each ear. As expected, the mean amplitudes of waves I-I' and V-V' both showed a decrease as stimulus intensity decreased, as seen in table 15. The variability in amplitude measurements for wave I-I' and V-V', as seen in SD values, ranged from 0.03-0.13, which is approximately the same as that seen for the absolute latency measurements.

Peak-to-peak amplitude of wave I-I' decreased from 0.19 μV at 80 dBnHL to 0.13 μV at 70 dBnHL. At stimulus intensities below 70 dBnHL, a replicable wave I was not present. In contrast, peak-to-peak amplitude of wave V-V' was recorded down to 30 dBnHL. Wave V peak-to-peak amplitude decreased from 0.49 μV at 80 dBnHL to 0.11 μV at 30 dBnHL. It should be noted that the mean wave V-V' peak-to-peak amplitude at 80 dBnHL was based on responses from 28 ears, whereas the mean V-V' amplitude value at 30 dBnHL was only based on 9 ears.

Table 14

Mean and Standard Deviation for Interaural Latency Differences of Wave V and I-V Interpeak Latency

		Interaural Latency Difference (ms)	
Stimulus Intensity		**Wave V**	**I-V**
80 dBnHL	**Mean**	**0.25**	**0.19**
	SD	(0.26)	(0.25)
	N	14	2
70 dBnHL	**Mean**	**0.23**	
	SD	(0.18)	
	N	14	
60 dBnHL	**Mean**	**0.39**	
	SD	(0.24)	
	N	14	
55 dBnHL	**Mean**	**0.42**	
	SD	(0.36)	
	N	14	
50 dBnHL	**Mean**	**0.56**	
	SD	(0.36)	
	N	13	
45 dBnHL	**Mean**	**1.12**	
	SD	(2.28)	
	N	13	
40 dBnHL	**Mean**	**0.75**	
	SD	(0.73)	
	N	12	
35 dBnHL	**Mean**	**1.37**	
	SD	(0.66)	
	N	4	

Wave V peak-to-peak amplitude was consistent in 28 ears down to 55 dBnHL and in the majority of ears (n=26) down to 40 dBnHL.

The mean wave V/I amplitude ratios ranged from 3.13 µV to 3.18 µV at 70 and 80 dBnHL, respectively. Wave V/I amplitude ratios could not be calculated below 70 dBnHL because a replicable wave I was not recorded. The variability for the wave V/I amplitude ratio was larger than that of peak-to-peak amplitudes, ranging from 0.83 to

2.19. As expected, these V/I amplitude ratios fell within the expected range of greater than 0.5 μV for normal hearing individuals.

ABR Thresholds

For all conductive hearing loss participants, ABR threshold was determined by the lowest stimulus intensity at which a replicable wave V could be identified. ABR thresholds for individual participants' as well as descriptive statistics (mean and standard deviation values) are shown in table 16 below. In conductive hearing loss participants, ABR thresholds ranged from 25 to 55 dBnHL. Mean ABR thresholds for right and left ears were 37.86 dBnHL and 33.93 dBnHL, respectively. In 28 ears, wave V was identifiable and replicable down to 55 dBnHL. It was interesting to note that wave V was present and replicable in the majority of ears (n=26) down to 40 dBnHL. The lowest ABR threshold, 25 dBnHL, was recorded in only 1 ear.

Table 15

Descriptive Statistic Values for Amplitude Values of Wave I-I', V-V', and V/I Ratio in Conductive Hearing Loss Group

		Peak-to-Peak Amplitude (μV)		Amplitude Ratio (μV)
Stimulus Intensity		**I-I'**	**V-V'**	**V/I**
80 dBnHL	**Mean**	**0.19**	**0.49**	**3.18**
	SD	(0.09)	(0.13)	(2.19)
	N	7	28	7
70 dBnHL	**Mean**	**0.13**	**0.37**	**3.13**
	SD	(0.06)	(0.10)	(0.83)
	N	2	28	2
60 dBnHL	**Mean**		**0.34**	
	SD		(0.09)	
	N		28	
55 dBnHL	**Mean**		**0.28**	
	SD		(0.07)	
	N		28	
50 dBnHL	**Mean**		**0.22**	
	SD		(0.05)	
	N		27	
45 dBnHL	**Mean**		**0.19**	
	SD		(0.07)	
	N		27	
40 dBnHL	**Mean**		**0.14**	
	SD		(0.05)	
	N		26	
35 dBnHL	**Mean**		**0.12**	
	SD		(0.03)	
	N		16	
30 dBnHL	**Mean**		**0.11**	
	SD		(0.03)	
	N		9	

Table 16

Individual Participants' ABR Thresholds as well as Mean and Standard Deviation Values for Conductive Hearing Loss Group

	ABR Threshold (dBnHL)	
Participant	**A_D**	**A_S**
15	55	35
16	40	30
17	30	35
18	40	30
19	40	30
20	35	25
21	40	30
22	40	40
23	35	35
24	35	45
25	30	30
26	35	40
27	35	40
28	40	30
Mean	**37.86**	**33.93**
SD	(6.11)	(5.61)

Comparison of ABR Results for the Normal Hearing and Simulated HL Groups

For all 28 participants, the ABR was recorded in both right and left ears to click stimuli beginning at 80 dBnHL. In both normal hearing and simulated hearing loss groups, stimulus intensity was decreased in 5-10 dB intervals until the participant's ABR threshold was determined. ABR latency and amplitude measurements were taken on each participant's data at each stimulus intensity. Each of these latency and amplitude results will be compared for normal hearing and simulated hearing loss groups below.

Absolute latency values of waves I, III, and V

As expected, mean absolute latency values for all waves were greater for the simulated hearing loss group than the normal hearing group. Mean absolute latency values for waves I, III, and V, and associated SD values, for normal hearing and simulated hearing loss groups can be seen in table 17 below. At a high intensity, 80 dBnHL, the largest mean absolute latency difference between the normal hearing and simulated hearing loss group occurred for wave V. Specifically, there was a 0.73 ms difference between normal hearing and simulated hearing loss groups for wave V. This was followed by a 0.48 ms difference of wave I and a 0.16 ms difference of wave III.

For all waves, mean absolute latency differences between groups increased as a function of stimulus intensity. Specifically, mean absolute latency difference of wave I increased from 0.48 ms to 0.57 as stimulus intensity was decreased from 80 dBnHL to 70 dBnHL. Similarly, mean absolute latency difference of wave III increased from 0.16 ms at 80 dBnHL to 0.52 ms at 70 dBnHL. Differences between mean absolute latency values for waves I and III could not be calculated at intensities 60 dBnHL because identifiable and replicable waves were not obtained at those intensities. Lastly, mean absolute latency differences for wave V increased from 0.73 ms at 80 dBnHL to 2.16 ms at 30 dBnHL.

Independent t-tests were performed to determine if there were significant differences in mean absolute latency values for wave V between the normal hearing group and simulated hearing loss group. The simulated hearing loss group had significantly longer mean wave V absolute latency values than the normal hearing loss group at stimulus intensities of 80 dBnHL ($t(27) = 9.27$, $p < 0.001$), 70 dBnHL ($t(27) = 9.99$, $p < 0.001$), and 60 dBnHL ($t(27) = 10.90$, $p < 0.001$). Analysis was limited to absolute latency of wave V at these specific stimulus intensities due to equal number of ears in both groups.

Table 17

Mean and SD for Absolute Latency Values of Wave I, III, and V for NH and Simulated Hearing Loss Groups

Stimulus Intensity		Absolute Latency (ms)					
		Wave I		Wave III		Wave V	
		NH	CHL	NH	CHL	NH	CHL
80 dBnHL	**Mean**	**1.70**	**2.18**	**3.94**	**4.10**	**5.73**	**6.46**
	SD	(0.10)	(0.20)	(0.20)	(0.36)	(0.21)	(0.36)
	N	28	7	28	11	28	28
70 dBnHL	**Mean**	**1.86**	**2.43**	**4.08**	**4.60**	**5.94**	**6.97**
	SD	(0.12)	(0.21)	(0.19)	(0.54)	(0.24)	(0.49)
	N	25	2	24	7	28	28
60 dBnHL	**Mean**	**2.03**		**4.23**		**6.20**	**7.49**
	SD	(0.13)		(0.29)		(0.30)	(0.55)
	N	12		16		28	28
50 dBnHL	**Mean**			**4.47**		**6.53**	**8.30**
	SD			(0.18)		(0.32)	(0.64)
	N			5		28	27
40 dBnHL	**Mean**					**7.03**	**9.20**
	SD					(0.47)	(0.71)
	N					28	26
30 dBnHL	**Mean**					**7.54**	**9.70**
	SD					(0.58)	(0.83)
	N					28	9

Interpeak and interaural latency values

Interpeak latencies for waves I-III, III-V, and I-V and interaural latency difference of IT5 and wave I-V were measured for both normal hearing and conductive hearing loss groups. Descriptive statistics (mean and standard deviation) for the various interpeak latency values and interaural latency values for clicks presented at intensities ranging from 70 to 80 dBnHL for normal hearing and conductive hearing loss groups are displayed in table 19. As expected, there were only minimal differences in any of the mean interpeak latency values between the two groups. Specifically, mean interpeak latency difference values for waves I-III ranged from 0.20 ms to 0.23 ms between normal hearing and simulated hearing loss groups. Similarly, mean interpeak latency difference values for waves III-V ranged from 0.29 ms to 0.34 ms, and 0.12 ms to 0.25 ms for waves I-V for the two groups, respectively.

Similarly, as expected there were minimal differences in the mean interaural latency values of IT5 and I-V between normal hearing and conductive hearing loss groups. Specifically, mean interaural latency differences for IT5 ranged from 0.10 to 0.16 ms between normal hearing and simulated hearing loss groups. Mean interaural latency difference for I-V at 80 dBnHL was 0.07 ms. Mean interaural latency differences for I-V could not be calculated at stimulus intensities less than 80 dBnHL because the conductive hearing loss group did not have an identifiable and replicable wave I at those intensities.

Table 18

Mean and SD for Interpeak Latency and Interaural Latency Values for Normal Hearing and Conductive Hearing Loss Groups

Interpeak Latency (ms)				
	80 dBnHL		**70 dBnHL**	
	NH	**CHL**	**NH**	**CHL**
I-III	2.24	2.01	2.23	2.03
III-V	1.80	2.09	1.83	2.17
I-V	4.03	3.91	4.06	3.81
Interaural Latency Difference (ms)				
	80 dBnHL		**70 dBnHL**	
	NH	**CHL**	**NH**	**CHL**
IT5	0.09	0.25	0.13	0.23
I-V	0.12	0.19	0.12	

Amplitude values

As expected, the mean peak-to-peak amplitude values for waves I-I’ and V-V’ were larger for the normal hearing group than the simulated hearing loss group. Mean peak-to-peak amplitude values for wave I-I’ and wave V-V’ and mean amplitude ratio V/I values as well as standard deviation values for normal hearing and simulated hearing loss groups are shown in table 18. The largest difference in mean peak-to-peak amplitude between normal hearing and simulated hearing loss groups occurred for wave V-V’. Specifically, at 80 dBnHL the mean peak-to-peak amplitude difference between the two groups for wave V-V’ was 0.20 μV, whereas the amplitude difference for wave I-I’ was 0.17 μV. Mean peak-to-peak amplitude difference for waves V-V’ and I-I’ did not change as a function of stimulus intensity. Wave V-V’ mean amplitude differences ranged from 0.20 μV to 0.28 μV. Similarly, wave I-I’ mean amplitude differences ranged from 0.10 μV to 0.17 μV. Mean wave I-I’ amplitude differences between the two groups could not be calculated below 70 dBnHL because identifiable and replicable wave I responses were not obtained in the simulated hearing loss group at those stimulus intensities.

Independent t-tests were performed to determine if there were significant differences in mean peak-to-peak amplitude values for wave V-V’ between the normal hearing group and simulated hearing loss group. The normal hearing group had significantly larger mean wave V-V’ peak-to-peak amplitude values than the simulated hearing loss group at stimulus intensities of 80 dBnHL ($t(27) = 4.95$, $p < 0.001$), 70 dBnHL ($t(27) = 6.37$, $p < 0.001$), and 60 dBnHL ($t(27) = 5.05$, $p < 0.001$). Analysis was limited to mean wave V'V' peak-to-peak amplitude values at these specific stimulus intensities due to equal number of ears in both groups.

The difference in mean wave V/I amplitude ratio values for normal hearing and simulated hearing loss groups was large for 80 dBnHL, 1.09 μV. However, there was only a small difference in mean wave V/I amplitude ratio values at 70 dBnHL, 0.24 μV.

Table 19

Mean and SD for Peak-to-Peak Wave I-I' and Wave V-V' Amplitude Values and V/I Amplitude Ratio for NH and Simulated Hearing Loss Groups

Stimulus Intensity		**Peak-to-Peak Amplitude (μV)**				**Amplitude Ratio (μV)**	
		I-I'		**V-V'**		**V/I**	
		NH	**CHL**	**NH**	**CHL**	**NH**	**CHL**
80 dBnHL	**Mean**	**0.36**	**0.19**	**0.69**	**0.49**	**2.09**	**3.18**
	SD	(0.11)	(0.09)	(0.17)	(0.13)	(0.80)	(2.19)
	N	28	7	28	28	28	7
70 dBnHL	**Mean**	**0.23**	**0.13**	**0.65**	**0.37**	**3.37**	**3.13**
	SD	(0.13)	(0.06)	(0.21)	(0.10)	(1.75)	(0.83)
	N	25	2	28	28	25	2
60 dBnHL	**Mean**	**0.15**		**0.58**	**0.34**	**4.44**	
	SD	(0.07)		(0.30)	(0.09)	(1.81)	
	N	12		28	28	12	
50 dBnHL	**Mean**			**0.43**	**0.22**		
	SD			(0.13)	(0.05)		
	N			28	27		
40 dBnHL	**Mean**			**0.42**	**0.14**		
	SD			(0.10)	(0.05)		
	N			28	26		
30 dBnHL	**Mean**			**0.37**	**0.11**		
	SD			(0.12)	(0.03)		
	N			28	9		

ABR Thresholds

Mean ABR thresholds and associated SD values for normal hearing and simulated hearing loss groups are displayed in table 20. In normal hearing participants, ABR thresholds ranged from 5 to 20 dBnHL. In contrast, ABR thresholds ranged from 25 to 55 dBnHL in simulated hearing loss participants. The lowest ABR threshold for the normal hearing group was 5 dBnHL (n=6), whereas the lowest ABR threshold for the simulated hearing loss group was 25 dBnHL (n=1). As expected, the mean ABR thresholds were poorer for the simulated hearing loss group than the normal hearing group. This pattern was true in both ears. The difference between mean ABR thresholds for normal hearing and simulated hearing loss groups ranged from 21.79 dB to 26.86 dB.

Table 20.

Mean and SD values for ABR Thresholds of Normal Hearing and Simulated Hearing Loss Groups

		ABR Threshold (dBnHL)	
		A_D	**A_S**
NH	**Mean**	**10**	**12.14**
	SD	(3.92)	(4.26)
CHL	**Mean**	**37.86**	**33.93**
	SD	(36.11)	(5.61)

Chapter 5

Discussion

This section will follow the same organization as the previous results chapter. The normal hearing participants' data will be presented first, followed by the data from the simulated conductive hearing loss group. Within these two sections, the results of ABR testing from this study will be compared to previous studies in the ABR literature. This includes comparison of the absolute latency measurements of waves I and V, interpeak and interaural latency measurements, peak-to-peak amplitude values of wave V-V', waves V/I amplitude ratio, and ABR thresholds. Lastly, goals and future implementation of the ABR data from this study will be discussed.

Normal Hearing Group

Absolute Latency Measurements for Waves I and V

In the present study, the click evoked ABRs were recorded at several intensities, from 80 dBnHL to participants' thresholds. Our results revealed that the mean absolute latencies of waves I and V increased as stimulus intensity decreased. Specifically, we had a 3.12 ms increase in wave V latency as stimulus intensity was decreased from 80 dBnHL to 10 dBnHL. Similarly, we recorded a 0.33 ms increase in wave I latency as stimulus intensity changed from 80 dBnHL to 60 dBnHL. These changes in absolute latency as a function of stimulus intensity was expected according to a number of studies (Don, Allen, & Starr, 1977; Picton, Stapells, & Campbell, 1981, Stockard et al., 1979; Weber & Fujikawa, 1977). Picton et al. (1981) reported that the absolute latencies of all three ABR waves (I, III, and V) increased as stimulus intensity decreased. A similar 70 dBnHL decrease in stimulus intensity resulted in a ~2.8 ms in wave V from ~5.4 ms at 80 dBnHL to ~8.2 ms at 10 dBnHL. The changes in wave I absolute latency as a function of stimulus intensity were not reported in Picton et al.'s study.

The mean absolute latency results of the current study were compared to previous studies in the ABR literature that investigated the effects of stimulus intensity on the absolute latencies of the various ABR waves (Don, Allen, & Starr, 1977; Picton, Stapells, & Campbell, 1981, Stockard et al., 1979; Weber & Fujikawa, 1977). These mean absolute latency comparisons are shown in table 21. Across all ABR studies, including the current study, a pattern of increases in absolute latencies of waves I and V as a function of stimulus intensity was consistent. However, mean absolute latency results of the current study were approximately 0.4 to 0.5 ms later across all stimulus intensities (Don, Allen, & Starr, 1977; Picton, Stapells, & Campbell, 1981, Stockard et al., 1979; Weber & Fujikawa, 1977). Additionally, these differences in mean absolute latency increased as stimulus intensity was decreased.

There are several differences in the stimulus and recording parameters of these various ABR studies that could account for these small differences in mean absolute latency in our current study. First, all five studies used different electrode montages and transducers when recording click-evoked ABRs. These specific electrode montages and transducers are described in table 21 below. Second, Weber and Fujikawa (1977), Don, Allen, and Starr (1977), and Picton et al. (1981) employed slow stimulus rates of 13.3/sec, 10/sec, and 11/sec for their click stimuli, whereas the current study used a stimulus rate of 19.1/sec. Additionally, these studies used different stimulus polarities including rarefaction, condensation, and alternating. Lastly, the current study reported stimulus intensity in dBnHL, whereas previous ABR studies reported stimulus intensity in dB SL (sensation level) (Don, Allen & Starr, 1977; Stockard et al., 1979; Weber & Fujikawa, 1977). In order to compare our data to the ABR literature, we established a conversion factor to allow us to convert our dBnHL units into dB SL units. This was a 1 to 1 conversion factor such that 30 dBnHL would equal 30 dB SL. The conversion between dBnHL and dB SL values necessary for comparison purposes could account, at least in part, for the differences seen in the latency values across studies. Overall, mean absolute latency results of the current study demonstrate the same pattern of increase in latencies to decreases in stimulus intensity. However, due to differences in the stimulus and recording parameters of the various ABR studies, the mean absolute latency results of the current study were slightly later across all stimulus intensities.

Table 21.

Comparison of Mean Absolute Latencies in the Current Study and Previous ABR Studies

	Absolute Latency (ms)									
	Current Study		**Weber & Fujikawa, 1977[1]**		**Don, Allen, & Starr, 1977[2]**		**Stockard et al., 1979[3]**		**Picton, Stapells, & Campbell, 1981[4]**	
Stimulus Intensity	**Wave I**	**Wave V**	**Wave I**	**Wave V**	**Wave I**	**Wave V**	**Wave I**	**Wave V**	**Wave I**	**Wave V**
80 dB SL	1.70	5.73								5.4
70 dB SL	1.86	5.94					1.70	5.80		5.5
60 dB SL	2.03	6.20		5.84		5.95	1.90	6.0		5.8
50 dB SL		6.53		6.04		6.3	2.0	6.10		6.1
40 dB SL		7.03		6.34		6.75	2.8	6.40		6.5
30 dB SL		7.54		6.87		7.3	2.9	6.80		7.0
20 dB SL		8.32		7.21						7.5
10 dB SL		8.85		7.87						8.2

1. 22 NH adults (mean age 24.5 years), Sennheisser 414X earphone, 13.3/sec, electrode montage: contralateral earlobe (ground), vertex (+), ipsilateral mastoid (-)
2. 6 NH adults (18-34 years), TDH 39 w/ MX-41 AR cushion, 10/sec, condensation polarity, electrode montage: vertex (+), left earlobe (-)
3. 64 NH adults (18-75 years), TDH 39 headphones, rarefaction polarity, electrode montage: C7 spinous process (ground), vertex (+), medial side of both earlobes (-)
4. Alternating polarity, 11/sec, electrode montage: vertex (+), ipsilateral mastoid (-)

Interpeak and Interaural Latencies

In addition to absolute latency measurements, the mean interpeak latencies of waves I-III, III-V and I-V were measured at various stimulus intensities (60 to 80 dBnHL). As expected, there were essentially no changes in these mean interpeak latency values across all stimulus intensities. This finding was especially true for the mean wave I-V interpeak latency which ranged from 4.01 ms to 4.06 ms at all stimulus intensities. The mean interpeak latency results in the current study are in good agreement with Picton et al. (1981). Picton and colleagues found no significant shifts in all mean interpeak latency measurements at high stimulus intensities, 70 and 80 dBnHL. They reported a mean wave I-V interpeak latency of approximately 4.02 ms at both stimulus intensities.

Similar to interpeak latency, the mean interaural latency results from the current study are in good agreement with the ABR literature. Previous studies on interaural latency values for wave V and I-V have established a normative range for acceptable interaural latency differences. In adults with normal hearing and normal oto-neurologic function, the maximum acceptable interaural difference for wave V absolute latency and I-V interpeak latency ranges from 0.2 to 0.4 ms (Bauch, Olsen & Pool, 1996; Don & Kwong, 2009). As expected, the mean interaural latency differences for wave V and waves I-V in the current study were below the permissible 0.4 ms interaural latency difference down to 10 dBnHL.

Peak-to-Peak Amplitude of Wave V-V' and Wave V/I Amplitude Ratio

In the current study, the effects of stimulus intensity on the peak-to-peak amplitude of wave V-V' showed an overall decrease in amplitude with decreases in stimulus intensity. According to a previous study on the effect of stimulus intensity on the peak-to-peak amplitude of wave V-V', this decrease in amplitude was expected (Picton, Stapells, & Campbell, 1981). Specifically, the results of the current study demonstrated a 0.51μV decrease in the mean wave V-V' amplitude as stimulus intensity was decreased from 80 dBnHL to 10 dBnHL. Picton et al. (1981) reported that the peak-to-peak amplitude of wave V-V' decreased as a function of stimulus intensity. A similar 70 dBnHL decrease in stimulus intensity resulted in a ~0.45 μV decrease in wave V-V' amplitude from ~0.6 μV at 80 dBnHL to ~0.15 μV at 10 dBnHL. When mean wave V-V' peak-to-peak amplitude results of the current study were compared to previous data from Picton et al. (1981), similar mean peak-to-peak amplitude values for wave V-V' were found across the two studies. The differences in mean wave V-V' amplitude values between these two studies were less than or equal to 0.1 μV. These mean wave V-V' peak-to-peak amplitude comparisons from the current study and Picton et al.'s (1981) study can be seen in table 22 below.

In addition to peak-to-peak amplitude of wave V-V', the V/I amplitude ratio was calculated from the peak-to-peak amplitude values for these two waves. Don and Kwong (2009) reported that any wave V/I amplitude ratio measurement less than 0.5 μV is considered abnormal and indicative of retrocochlear pathology. Based on these ABR findings, we used a greater than 0.5 μV criterion for the V/I amplitude ratio indicating a normal functioning system. As expected, all mean wave V/I amplitude ratios in the current study were substantially greater than the 0.5 μV criterion, ranging from 2.09 to 4.44 μV across all stimulus intensities (60 to 80 dBnHL). Therefore, all mean wave V/I amplitude ratio values were in good agreement with the ABR literature.

Table 22

Comparison of Peak-to-Peak Wave V-V' Amplitudes in the Current Study and Picton et al., 1981

Peak-to-Peak Amplitude Wave V-V' (μV)		
Stimulus Intensity	**Current Study**	**Picton, Stapells, & Campbell, 1981[1]**
80 dB SL	0.69	0.6
70 dB SL	0.65	0.55
60 dB SL	0.58	0.5
50 dB SL	0.43	0.45
40 dB SL	0.42	0.4
30 dB SL	0.37	0.33
20 dB SL	0.26	0.28
10 dB SL	0.18	0.15

ABR Thresholds

For all normal hearing participants, ABR threshold was determined by the lowest stimulus intensity at which a replicable wave V could be identified. These ABR thresholds ranged from 5 to 20 dBnHL. In all 28 ears, wave V was identifiable and replicable down to 20 dBnHL. In addition, wave V was present and replicable in the majority of ears (n=26) down to 15 dBnHL. These ABR threshold results for normal hearing participants were in agreement with findings from Picton et al. (1981). Picton and colleagues reported that wave V was easily recognizable in normal subjects to within 20 dB of threshold (Picton et al., 1981). As expected, all participants in the present study had ABR thresholds within the normal hearing range and within 20 dB of threshold.

Simulated Conductive Hearing Loss Group

Absolute Latency Measurements for Wave V

In the present study, the click evoked ABRs were recorded at several intensities, from 80 dBnHL to participants' thresholds. Our results revealed that the mean absolute latencies of waves I and V increased as stimulus intensity decreased. Specifically, we had a 2.74 ms increase in wave V latency as stimulus intensity was decreased from 80 dBnHL to 40 dBnHL. Similarly, we recorded a 0.25 ms increase in wave I latency as stimulus intensity changed from 80 dBnHL to 70 dBnHL. It is important to note that wave I absolute latency could not be measured at lower stimulus intensities because wave I disappeared at 60 dBnHL. These changes in absolute latency as a function of stimulus intensity were expected according to a previous simulated conductive hearing loss study (van der Drift, Brocaar, & Zanten, 1988). van der Drift and colleagues (1988) reported that the absolute latency of wave V increased as stimulus intensity decreased. A similar 40 dBnHL decrease in stimulus intensity resulted in a ~2.8 ms in wave V from ~6.5 ms at 80 dBnHL to ~9.3 ms at 40 dBnHL. The changes in wave I absolute latency as a function of stimulus intensity were not reported in van der Drift et al.'s study.

When mean absolute latency results of the current study were compared to previous data from van der Drift et al. (1988), similar mean latencies for wave V were found across the two studies. These mean absolute latency comparisons are summarized in table 23.

Interpeak and Interaural Latencies

In addition to absolute latency measurements, the mean interpeak latencies of waves I-III, III-V and I-V were measured at various stimulus intensities (70 to 80 dBnHL). In ABR literature, it has been reported that conductive hearing loss, in general, causes a prolongation in the absolute latencies of all ABR waves (Hood, 1998).

Table 23

Comparison of Mean Absolute Latency Values from Current Study and van der Drift et al. (1988)

	Absolute Latency (ms)			
	Current Study		**van der Drift, Brocaar & Zanten, 1988**	
Stimulus Intensity	**Wave I**	**Wave V**	**Wave I**	**Wave V**
80 dB SL	2.18	6.46		6.5
70 dB SL	2.43	6.97		6.95
60 dB SL		7.49		7.4
50 dB SL		8.30		8.0
40 dB SL		9.20		9.3

However, interpeak latencies remain within normal limits (Hood, 1998). As expected, there were essentially no changes in these mean interpeak latency values across all stimulus intensities. This was especially true for mean interpeak latency of I-III which ranged from 2.01 ms to 2.03 ms. All interpeak latencies could not be measured below 70 dBnHL because early components, wave I and III, disappeared at 60 dBnHL

The current study also measured the interaural latency differences of wave V and waves I-V. The mean interaural latency difference values for wave V fell within the expected normative range of less than or equal to 0.4 ms at stimulus intensities from 60 dBnHL to 80 dBnHL (Bauch et al, 1996; Don & Kwong, 2009). At the lower stimulus intensities, the mean interaural difference values for wave V increased as a function of stimulus intensity. Additionally, mean interaural latency difference for waves I-V fell within the normative range. It is important to note that the mean interaural difference for waves I-V could only be calculated for the highest stimulus intensity (80 dBnHL) because an identifiable and replicable wave I response could not be obtained at lower stimulus intensities.

Peak-to-Peak Amplitude of Wave V-V' and Wave V/I Amplitude Ratio

In the current study, the effects of stimulus intensity on the peak-to-peak amplitude of wave V-V' showed an overall decrease in amplitude with decreases in stimulus intensity. Specifically, mean peak-to-peak amplitude of wave V-V' decreased from 0.49 μV at 80 dBnHL to 0.11 μV at 30 dBnHL. Based on our review of the ABR literature, previous studies have not investigated the effects of conductive hearing loss on the peak-to-peak amplitude of wave V-V'. Therefore, comparisons to the ABR literature cannot be made.

In addition to peak-to-peak amplitude of wave V-V', the V/I amplitude ratio was calculated from the peak-to-peak amplitude values for these two waves. Don and Kwong (2009) reported that any wave V/I amplitude ratio measurement less than 0.5 μV is considered abnormal and indicative of retrocochlear pathology. Based on these ABR findings, we used a greater than 0.5 μV criterion for the V/I amplitude ratio. All mean wave V/I amplitude ratios were substantially greater than the 0.5 μV criterion, ranging from 3.13 to 3.18 μV across all stimulus intensities (70 to 80 dBnHL). Mean wave V/I amplitude ratio values could not be calculated below 70 dBnHL because identifiable and replicable wave I responses were not seen at stimulus intensities below 70 dBnHL.

ABR Thresholds

In the present study, ABR threshold for conductive hearing loss participants was determined by the lowest stimulus intensity at which a replicable wave V could be identified. These ABR thresholds ranged from 25 to 55 dBnHL. In all 28 ears, wave V was identifiable and replicable down to 55 dBnHL. In addition, wave V was present and replicable in the majority of ears (n=26) down to 40 dBnHL. The lowest ABR threshold, 25 dBnHL, was recorded only in one ear. For all simulated conductive hearing loss participants, ABR thresholds were in good agreement with pure tone air conduction thresholds.

Goals and Future Implications for the Study

The ultimate goal of the project was to develop a parametric approach to generating simulated responses for a commercially available Auditory Brainstem Response (ABR) recording simulator, ISAO by Intelligent Hearing Systems. The simulator currently relies on a library of prerecorded responses obtained at various discrete recording parameters such as intensities, rates, and frequencies. Although the library can be expanded and modified by users, it does not encompass the broad and continuous range of acquisition parameters that can be selected during an ABR audiometric evaluation. In order to address this issue, the parameters extracted from the literature and this study will serve as the basis for developing functions of response characteristics such as peak latency and amplitude as well as recording parameters like intensity, rate and stimulus characteristics. These functions will then be used to synthesize responses on the fly based on the detected stimulus characteristics and various noise recording conditions. This approach will provide a more generalized simulation technique that will not require a discrete library of sample recordings.

Following the current study, further research should be conducted to determine the effects of other stimulus parameters on the ABR. These stimulus parameters include rate, polarity, and frequency. The data from these projects can be used to develop additional functions of response characteristics for simulation. Ultimately, the data from this study and future studies will be used to help audiology faculty train their graduate students in simulating many of the different ABR findings that they may see in their clinical practice. This will expose students to various types of pathologies, such as retrocochlear pathologies, that may not be readily accessible in their academic programs and allow them to practice their clinical skills until they are ready to work with actual patients.

APPENDIX A

Certificate of Calibration

Kimmetrics

Sales and Service

This is to certify on February 8, 2018

Make and Model IHS SmartEP

Serial Number IHS 5466

was calibrated by Kimmetrics Sales and Service.

As shown on the reverse side of this certificate, the above listed instrument complies/does not comply with:

	Complies With	Does Not Comply
ANSI S3.6-2010 Audiometer Specifications	☐	☐
ANSI S3.6-1996 Audiometer Specifications	☐	☐
ANSI S3.6-1989 Audiometer Specifications	☐	☐
ANSI S3.39-1987 (R 2007) Immittance Specifications	☐	☐
ANSI S.322-2009 Hearing Aid Specifications	☐	☐
ANSI S3.46-1997 (R 2007) Real Ear Specifications	☐	☐
ANSI S3.45-2009 Vestibular Testing Specifications	☐	☐
OSHA 1983 Exhaustive Calibration Specifications	☐	☐
Manufacturer Specifications	☒	☐

Signature [signature]

Kimmetrics Sales and Service
Hagerstown, MD
www.kimmetrics.com

09/2012

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Excellence in Service-Support-Expertise

Certificate of Auditory Evoked Potential System Calibration

OWNER Towson University MAKE I H S MODEL SMART EP SERIAL NO. IHS5460

Stimulus								
Frequency, Hz		Insert Earphones dB [redacted] PP at 80dB		TDH Earphones dB Deviation*		Distortion THD dB Down	Bone dB Deviation*
Indicated	Actual	Left	Right	Left	Right		
500	500	101.5	101.9	-	-	-	-
1000	1000	94.3	94.5	-	-	-	-
2000	2000	95	95.3	-	-	-	-
3000	3000	97.1	97.3	-	-	N/A	
4000	4000	101.5	101.4	-	-	-	-
8000	8000	80.6	81.4	-	-	N/A	
NOISE	N/A	80.6	80.3	-	-	N/A	N/A
CLICK	100 us	112.2	112.4	-	-	N/A	-

NOTE: * Deviations are from dB HL (ANSI or ISO Standards) or Manufacturers; dB SPL, dB P.E. SPL, or dB nHL Specifications.

Technical Specifications	Pass	Fail
Computer Service	X	
System Loop Test - EEG, average.	X	
Electrode Impedance - 1K, 2K, 3K	X	
Click Polarity - Cond., Rare., Alt.	X	
Click Duration - 100 us	X	
Repetition Rate - 100/Sec = 10 ms	X	
Stimulus Delay - TDH=0, ER3A=1.0 ms	X	
Phone Ringing/Clipping @ Max SPL	X	
Unwanted Sounds - 70 dB Down	X	
Ground Integrity - Line Cord, Outlet	X	
Mechanical Integrity	X	

Attenuator Linearity, dB Deviation

Dial Indication	120	115	110	105	100	95	90	85	80	75	70	65	60	55	50	45	40	35	30	25	20	<20
Left	-	-	-	-	-	91.5	86.5	81.4	76.5	71.4	0 Ref.	61.4	56.4	51.3	46.5	41.6	36.7	31.7	26.9	22.1	18.1	N/A
Right	-	-	-	-	-	91.6	86.7	81.6	76.7	71.8	0 Ref.	61.7	56.7	51.6	46.7	41.7	36.7	31.8	27.1	22.5	18.5	N/A

Date of Calibration 02/08/2018

Certified By Jim Kimmel

7502 Connelley Dr Ste 106 Hanover, MD (800) 366-4616

SLM Larson Davis 824 S/n 2553

Mic LD 2575 s/n 1540

LD AMC 493 s/n 5336

Comments:

Phone Type	-
Impedance	-

KSS 1019 09/12

Calibration of Polarity Reversal: Rarefaction (top line), Condensation (middle line), Alternating (bottom line)

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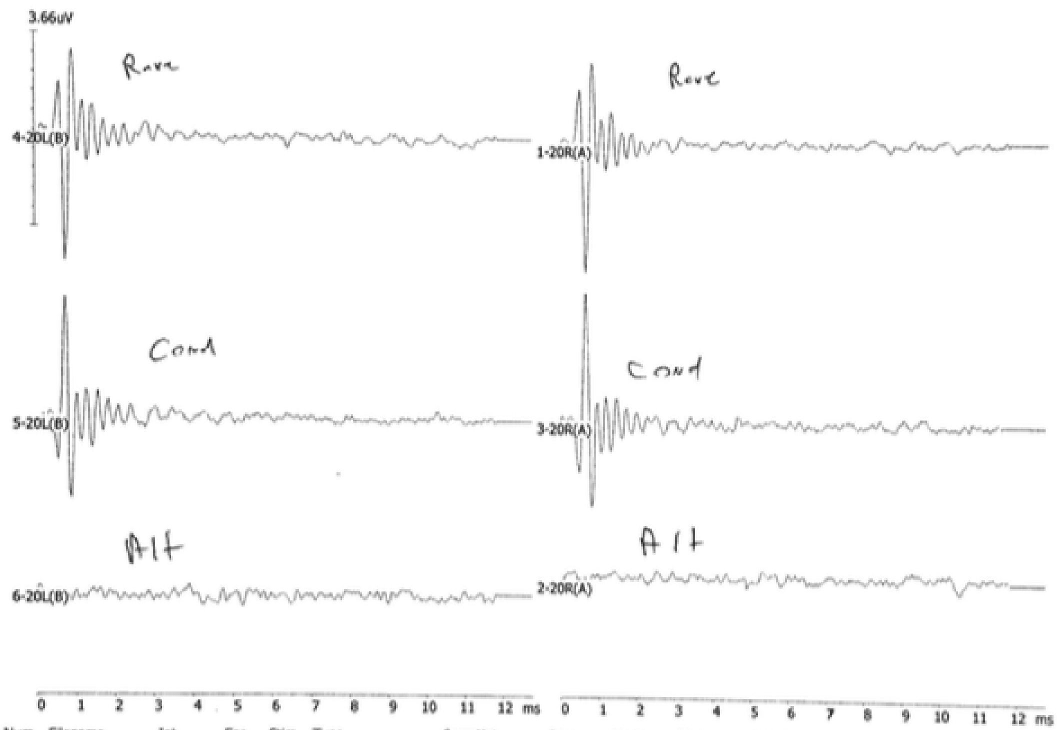
ID: XX Page: Acq Test Date: Feb. 08, 2018 DOB: Age: (DOB empty) Report: Feb. 08, 2018



Num	Filename	Int	Ear	Stim.	Type	Swps/Art	Rate	Mode	PP Amp	SNR	RN	Gain	Filters
1	NEW	20nHL	R	Inst	Click	315/1	11.1	Rare	3.56	0.47	0.18	100	100-3000Hz
2	NEW	20nHL	R	Inst	Click	193/1	11.1	Altr	0.36	0.49	0.21	100	100-3000Hz
3	NEW	20nHL	R	Inst	Click	230/1	11.1	Cond	3.66	0.46	0.22	100	100-3000Hz
5	NEW	20nHL	L	Inst	Click	215/1	11.1	Cond	3.41	0.38	0.23	100	100-3000Hz
6	NEW	20nHL	L	Inst	Click	173/1	11.1	Altr	0.35	0.55	0.23	100	100-3000Hz

System SNR & RN Region: 4.00 - 9.00 ms (*)-indicates different region used

Num	Int	Ear	Peaks: Latency(ms) | Amp(uV) (AR=Amp Ratio)
1	20	R	
2	20	R	
3	20	R	
5	20	L	
6	20	L	

APPENDIX B

INFORMED CONSENT FORM

PRINCIPAL INVESTIGATOR: Molly Bishop, B.A. (Audiology Doctoral Student)
PHONE: (410)-274-8760

Purpose of the Study:
This study is designed to obtain click-evoked auditory brainstem response (ABR) data in order to create new AEP Libraries in the Intelligent Hearing System (IHS) Simulator Unit as well as to provide actual ABR data which can be used to model the effects of different degrees of conductive hearing loss on the response properties of the ABR.

Procedures:
Participants will participate in one test session lasting approximately sixty to ninety minutes. First, acoustic immittance testing, including tympanometry and contralateral acoustic reflex testing, will be conducted to determine middle ear function. Tympanometry is a routine clinical test of how well the eardrum moves in response to varying amounts of air pressure in the ear canal. A probe will be placed into the participant's ear and will push air into the ear for a few seconds. The participant will sit still and quiet during the test. This test will show is the eardrum is moving properly, is too stiff, moves too much, or has a hole in it. Acoustic reflex testing is a routine clinical test of a tiny muscle in the middle ear. This muscle tightens when you hear a loud sound and can be affected by hearing loss. A sound will be played through a probe in the participant's ear and a device will record the reflex. Again, the participant will sit still and quiet during the test. Next, behavioral air-conduction and bone-conduction thresholds will be measured for 250-8000 Hz bilaterally. The participant will hear a series of tones and will be instructed to press a button as soon as the tone comes on, even if the tone is very faint. Air-conduction thresholds will be measured using in-the-ear earphones and bone-conduction thresholds will be measured using a bone conduction oscillator on the mastoid bone, behind the ear. If participant is randomly assigned into simulated hearing loss group, thresholds will be measured a second time with moleskin placed in the ER3A insert tubing. Lastly, click-evoked ABR testing will be performed. Participants will be instructed to relax or sleep while sitting in a lazyboy recliner. Standard surface EEG disk electrodes will be attached to the following locations on the scalp: forehead, center of scalp and right and left earlobes. The areas will be prepped using an alcohol wipe and a Nuprep skin prep gel. Click-evoked ABRs will be recorded beginning at 80 dBnHL. Stimulus intensity will be decreased until the participant's ABR threshold is determined. All testing is being completed as part of the principle investigator's doctoral dissertation and will be conducted by the principle investigator under the supervision of faculty mentor, Dr. Peggy Korczak.

Risks/Discomfort:
There are no known risks associated with participation in the study. Should the testing become uncomfortable to you, it will be terminated immediately.

Benefits:
It is hoped that the results of this study will be used to create new AEP Libraries in the IHS Simulator unit, so that the audiology graduate students can use this unit to better understand the effects of conductive hearing loss on the ABR.

Alternatives to Participation:
Participation in this study is voluntary. You are free to withdraw or discontinue participation at any time.

Cost Compensation:
Participation in this study will involve no costs or payments to you.

Confidentiality:

All information collected during the study period will be kept strictly confidential. You will be identified through random identification numbers. No publications or reports from this project will include identifying information on any participant. If you agree to join this study, please sign your name below.

_____ I have read and understood the information on this form.

_____ I have had the information on this form explained to me.

______________________________________ ______________

Subject's Signature Date

______________________________________ ______________

Witness to Consent Procedures Date

______________________________________ ______________

Principal Investigator Date

If you have any questions regarding this study please contact Molly Bishop (410)-274-8760, Dr. Peggy Korczak (410)-704-5903 or the Institutional Review Board Chairperson, Dr. Elizabeth Katz, Office of University Research Services, 8000 York Road, Towson University, Towson, Maryland 21252; phone (410) 704-2236.

THIS PROJECT HAS BEEN REVIEWED BY THE INSTITUTIONAL REVIEW BOARD FOR THE PROTECTION OF HUMAN PARTICIPANTS AT TOWSON UNIVERSITY.

**If investigator is not the person who will witness participant's signature, then the person administering the informed consent should write his/her name and title on the "witness" line.

APPENDIX C

Table 1. *Absolute Latency of Waves, I, III, and V at Three Intensity Levels in Normal Hearing Group*

	80 dBnHL			70 dBnHL			60 dBnHL		
Ear	Wave I	Wave III	Wave V	Wave I	Wave III	Wave V	Wave I	Wave III	Wave V
1	1.58	3.58	5.68	1.8	3.85	5.88		4.13	6.18
2	1.73	4.03	5.68	1.93	4.13	5.83			6.03
3	1.73	4.03	5.68	1.93	4.03	5.9			6.23
4	1.8	3.83	5.72	1.93	4.13	5.83		4.22	6.08
5	1.55	3.78	5.4	1.68	4	5.55	1.95	4.05	5.7
6	1.75	4.1	5.45	1.83	4.13	6.05			6.35
7	1.73	3.93	5.7	1.75	4.05	5.88	2.17	4.3	6.1
8	1.55	3.78	5.5	1.83	3.93	5.65	2.17	4.03	5.88
9	1.75	3.85	5.68	2.2	4.1	5.88	2.1	4.33	6.05
10	1.73	4.08	6.08	1.83	4.35	6.33	2.2	4.83	6.55
11	1.9	3.9	5.72			5.9			6.15
12	1.55	3.68	5.65	1.73	3.8	5.75		3.88	5.9
13	1.8	4.33	6.15	1.98		6.3			6.85
14	1.58	3.73	5.6	1.73	3.83	5.7	1.83	4.08	5.9
15	1.55	3.83	5.78	1.8	4.1	5.85	1.83	4.08	6.23
16	1.85	4.03	5.7	1.83	4.13	6.1			6.15
17	1.75	4.03	5.88	2	4.38	6.08			6.3
18	1.7	3.75	5.72	1.9	3.95	5.88	2.1	4.13	6.1
19	1.63	3.7	5.45	1.78	3.95	5.68	2.08	4.13	5.93
20	1.78	4.05	5.88	2	4.22	6.28			6.68
21	1.65	3.98	5.72			6.18			6.15
22	1.65	3.85	5.5	1.83	4.05	5.68	2	4.38	5.9
23	1.73	3.95	5.6	1.83	4.05	5.7			6.15
24	1.85	4.45	6.1	2.05	4.55	6.38		4.97	6.75
25	1.83	4.15	5.8			5.95			6.35
26	1.65	3.85	5.72	1.7	3.9	5.8	2	4.05	5.9
27	1.73	4.2	6.25	1.83	4.38	6.4			6.78
28	1.65	3.83	5.7	1.78	3.93	5.85	1.88	4.05	6.23

Note. All values measured in milliseconds (ms).

Table 2. *Absolute Latency of Waves, I, III, and V at Three Intensity Levels in Normal Hearing Group*

	50 dBnHL			40 dBnHL			30 dBnHL		
Ear	Wave I	Wave III	Wave V	Wave I	Wave III	Wave V	Wave I	Wave III	Wave V
1		4.75	6.43		4.97	7		5.53	7.38
2			6.45			6.68			7.05
3			6.5			6.98			7.5
4			6.35			6.7			7.28
5			6.1			6.53			6.9
6			6.68			7			7.48
7			6.33			6.75			7.15
8		4.4	6.13			6.6			7.15
9			6.4			6.83			7.48
10			7.1			7.9			8.55
11			6.53			6.95			7.28
12		4.43	6.18			6.5			6.93
13			7.3			8.13			8.93
14			6.28			7.05			7.48
15			6.6			7			7.43
16			6.6			7.13			7.68
17			6.63			7.25			7.73
18		4.5	6.25			6.63			7.13
19			6.18			6.63			7
20			7.08			7.43			7.5
21			6.4			6.65			6.98
22			6.33			6.93			7.65
23			6.48			6.98			7.53
24			6.9			8.1			9.1
25			6.63			7.1			7.38
26		4.25	6.18			6.53			7
27			7.18			7.95			8.6
28			6.53			6.9			7.73

Note. All values measured in milliseconds (ms).

Table 3. *Absolute Latency of Waves, I, III, and V at Three Intensity Levels in Normal Hearing Group*

	25 dBnHL			20 dBnHL			15 dBnHL		
Ear	Wave I	Wave III	Wave V	Wave I	Wave III	Wave V	Wave I	Wave III	Wave V
1			7.65			7.98			8.45
2			7.6			8			8.82
3			7.98			8.48			9.1
4			7.53			7.98			8.15
5			7.13			7.38			7.78
6			8.1			8.35			8.65
7			7.33			7.5			7.9
8			7.65			8.2			8.73
9			7.73			8.07			8.35
10			9.23			9.7			
11			7.55			7.85			8.13
12			7.2			7.55			8.03
13			9.35			10.03			10.45
14			7.9			8.32			8.73
15			7.7			7.95			8.32
16			7.9			8.53			8.98
17			8.05			8.75			9.35
18			7.45			8			8.38
19			7.2			7.55			8.05
20			8.55			8.57			9.4
21			7.28			7.5			7.7
22			8.45			8.8			9.57
23			7.7			7.9			
24			9.57			10.3			10.65
25			7.65			8.1			8.57
26			7.23			7.63			7.98
27			9.23			9.38			10.05
28			8.23			8.57			9.03

Note. All values measured in milliseconds (ms).

Table 4. *Absolute Latency of Waves, I, III, and V at Two Intensity Levels in Normal Hearing Group*

	10 dBnHL			5 dBnHL		
Ear	Wave I	Wave III	Wave V	Wave I	Wave III	Wave V
1			8.75			
2						
3			9.45			
4			9.05			9.45
5			7.88			
6			9.13			
7			8.53			8.88
8			9.4			
9						
10						
11			8.38			
12			8.23			9.3
13						
14			8.88			9.4
15			8.75			
16						
17						
18			8.98			
19			8.32			
20						
21			8.32			8.98
22						
23						
24						
25			9.7			
26			8.38			8.53
27			10.25			
28						

Note. All values measured in milliseconds (ms).

APPENDIX D

Table 5. *Interpeak Latency of Waves I-III, III-V, and I-V at Three Intensity Levels in NH Group*

	80 dBnHL			70 dBnHL			60 dBnHL		
Ear	I-III	III-V	I-V	I-III	III-V	I-V	I-III	III-V	I-V
1	2	2.1	4.1	2.05	2.03	4.08		2.05	
2	2.3	1.65	3.95	2.2	1.7	3.9			
3	2.3	1.65	3.95	2.1	1.88	3.98			
4	2.03	1.9	3.93	2.2	1.7	3.9		1.85	
5	2.22	1.63	3.85	2.33	1.55	3.88	2.1	1.65	3.75
6	2.35	1.35	3.7	2.3	1.92	4.22			
7	2.2	1.78	3.98	2.3	1.83	4.13	2.13	1.8	3.93
8	2.22	1.73	3.95	2.1	1.73	3.83	1.85	1.85	3.7
9	2.1	1.82	3.93	1.9	1.78	3.68	2.23	1.72	3.95
10	2.35	2	4.35	2.52	1.98	4.5	2.63	1.72	4.35
11	2	1.82	3.83						
12	2.13	1.98	4.1	2.07	1.95	4.03		2.03	
13	2.53	1.83	4.35						
14	2.15	1.87	4.02	2.1	1.88	3.98	2.25	1.83	4.08
15	2.28	1.95	4.23	2.27	1.75	4.02	2.25	2.15	4.4
16	2.18	1.67	3.85	2.3	1.97	4.27			
17	2.28	1.85	4.13	2.38	1.7	4.08			
18	2.05	1.97	4.02	2.05	1.92	3.98	2.03	1.97	4
19	2.08	1.75	3.83	2.18	1.72	3.9	2.05	1.8	3.85
20	2.28	1.83	4.1	2.22	2.05	4.28			
21	2.33	1.75	4.07						
22	2.2	1.65	3.85	2.22	1.63	3.85	2.38	1.53	3.9
23	2.23	1.65	3.87	2.22	1.65	3.87			
24	2.6	1.65	4.25	2.5	1.83	4.33		1.78	
25	2.33	1.65	3.97						
26	2.2	1.87	4.07	2.2	1.9	4.1	2.05	1.85	3.9
27	2.48	2.05	4.53	2.55	2.03	4.58			
28	2.18	1.88	4.05	2.15	1.92	4.07	2.17	2.17	4.35

Note. All values measured in milliseconds (ms).

Table 6. *Interpeak Latency of Waves I-III, III-V, and I-V at Three Intensity Levels in NH Group*

	50 dBnHL			40 dBnHL			30 dBnHL		
Ear	I-III	III-V	I-V	I-III	III-V	I-V	I-III	III-V	I-V
1		1.67			2.03			1.85	
2									
3									
4									
5									
6									
7									
8		1.72							
9									
10									
11									
12		1.75							
13									
14									
15									
16									
17									
18		1.75							
19									
20									
21									
22									
23									
24									
25									
26		1.92							
27									
28									

Note. All values measured in milliseconds (ms).

APPENDIX E

Table 7. *Interaural Latency Difference of Wave V and Wave I-V at Three Stimulus Levels in NH Group*

	80 dBnHL		70 dBnHL		60 dBnHL	
Participant	Wave V	Wave I-V	Wave V	Wave I-V	Wave V	Wave I-V
1	0.1	0.13	0.03	0.06	0.05	
2	0.02	0.1	0.27	0.37	0.12	
3	0.2	0.18	0.18	0.1	0.07	
4	0	0.09	0.05	0.08	0.02	
5	0.05	0.02	0.13	0.02	0.23	0.1
6	0.43	0.4	0.23	0.06	0.33	
7	0.02	0.09	0.3		0.05	
8	0	0.1	0.03	0.02	0.02	
9	0.08	0.06	0.18	0.19	0.1	
10	0.02	0.1	0.05	0.17	0.2	
11	0.08	0.14	0.1		0.2	
12	0.07	0.03	0.05	0.07	0	
13	0.1	0.18	0.1	0.26	0.1	
14	0.1	0.03	0.05	0.09	0.33	0.27

Note. All values measured in milliseconds (ms).

Table 8. *Interaural Latency Difference of Wave V and Wave I-V at Three Stimulus Levels in NH Group*

	50 dBnHL		40 dBnHL		30 dBnHL	
Participant	Wave V	Wave I-V	Wave V	Wave I-V	Wave V	Wave I-V
1	0.17		0		0.05	
2	0.15		0.45		0.63	
3	0.13		0.27		0.23	
4	0.1		0.07		0.15	
5	0.08		0.1		0.1	
6	0.4		0.43		0.02	
7	0.07		0.1		0.17	
8	0.2		0.33		0.5	
9	0.08		0.15		0.05	
10	0.11		0.2		0.55	
11	0.1		0.15		0.1	
12	0		0.03		0.07	
13	0.12		0.18		0.33	
14	0.25		0.15		0.25	

Note. All values measured in milliseconds (ms).

Table 9. *Interaural Latency Difference of Wave V and Wave I-V at Three Stimulus Levels in NH Group*

	25 dBnHL		20 dBnHL		15 dBnHL	
Participant	Wave V	Wave I-V	Wave V	Wave I-V	Wave V	Wave I-V
1	0.05		0.03		0.13	
2	0.3		0.53		0.16	
3	0.07		0.27		0.25	
4	0.08		0.02		0.23	
5	0.07		0.17		0.27	
6	0.45		0.22		0.74	
7	0.05		0		0.2	
8	0.8		0.6		0.84	
9	0.03		0.17			
10	0.34		0.6			
11	0.1		0.25		0.44	
12	0.03		0.08		0.05	
13	0.12		0.65		0.4	
14	0.33		0.25		0.3	

Note. All values measured in milliseconds (ms).

Table 10. *Interaural Latency Difference of Wave V and Wave I-V at Two Stimulus Levels in NH Group*

	10 dBnHL		5 dBnHL	
Participant	Wave V	Wave I-V	Wave V	Wave I-V
1	0			
2				
3				
4	0.07			
5	0.44			
6				
7	0.21		0.1	
8				
9				
10				
11	1.32			
12	0.15		0.77	
13				
14				

Note. All values measured in milliseconds (ms).

APPENDIX F

Table 11. *Amplitude and Amplitude Ratios of Waves I and V at Three Intensity Levels in NH Group*

	80 dBnHL			70 dBnHL			60 dBnHL		
Ear	Wave I	Wave V	V/I Ratio	Wave I	Wave V	V/I Ratio	Wave I	Wave V	V/I Ratio
1	0.4	0.55	1.38	0.17	0.47	2.69		0.44	
2	0.19	0.92	4.85	0.11	0.44	4.17		0.47	
3	0.35	0.75	2.14	0.24	0.65	2.67		0.45	
4	0.38	1.1	2.86	0.37	1.03	2.81		0.65	
5	0.38	0.77	2.01	0.35	0.71	2.04	0.28	0.57	2
6	0.45	0.39	0.87	0.16	0.48	3.05		0.4	
7	0.24	0.58	2.4	0.19	0.39	2.03	0.09	0.5	5.3
8	0.33	0.66	2	0.15	0.63	4.31	0.13	0.52	3.84
9	0.31	0.65	2.06	0.16	0.68	4.22	0.09	0.52	5.9
10	0.3	0.7	2.37	0.07	0.55	7.94	0.07	0.55	8.31
11	0.32	0.69	2.17		0.87			0.81	
12	0.27	0.81	2.99	0.29	0.65	2.29		0.36	
13	0.15	0.4	2.63	0.12	0.54	4.53		0.4	
14	0.4	0.89	2.26	0.45	1.34	2.98	0.24	1.24	5.14
15	0.23	0.68	2.98	0.2	0.63	3.21	0.12	0.24	2.09
16	0.31	0.49	1.6	0.16	0.44	2.77		0.31	
17	0.31	0.85	2.76	0.18	0.84	4.72		0.66	
18	0.65	0.92	1.41	0.44	0.81	1.84	0.21	0.68	3.23
19	0.58	0.83	1.42	0.45	0.67	1.49	0.19	0.51	2.71
20	0.48	0.75	1.56	0.1	0.63	6.47		0.55	
21	0.25	0.67	2.69		0.77			0.54	
22	0.38	0.54	1.43	0.14	0.6	4.29	0.1	0.54	5.48
23	0.51	0.69	1.36	0.51	0.69	1.36		0.49	
24	0.23	0.42	1.83	0.22	0.32	1.42		1.78	
25	0.4	0.57	1.41		0.5			0.57	
26	0.39	0.66	1.69	0.27	0.54	1.98	0.09	0.44	5.07
27	0.46	0.52	1.12	0.2	0.41	2.05		0.29	
28	0.37	0.88	2.4	0.12	0.84	6.99	0.16	0.66	4.17

Note. All values measured in microvolts (μV)

Table 12. *Amplitude and Amplitude Ratios of Waves I and V at Three Intensity Levels in NH Group*

	50 dBnHL			40 dBnHL			30 dBnHL		
Ear	Wave I	Wave V	V/I Ratio	Wave I	Wave V	V/I Ratio	Wave I	Wave V	V/I Ratio
1		0.41			0.55			0.38	
2		0.35			0.34			0.36	
3		0.34			0.3			0.34	
4		0.58			0.5			0.62	
5		0.41			0.66			0.51	
6		0.28			0.34			0.29	
7		0.31			0.42			0.3	
8		0.51			0.48			0.4	
9		0.46			0.51			0.32	
10		0.46			0.42			0.33	
11		0.59			0.44			0.32	
12		0.51			0.41			0.38	
13		0.33			0.28			0.33	
14		0.85			0.6			0.68	
15		0.35			0.55			0.41	
16		0.23			0.29			0.12	
17		0.55			0.53			0.44	
18		0.58			0.42			0.47	
19		0.49			0.44			0.43	
20		0.35			0.36			0.41	
21		0.37			0.4			0.43	
22		0.44			0.36			0.32	
23		0.42			0.31			0.23	
24		0.37			0.36			0.24	
25		0.36			0.38			0.28	
26		0.37			0.33			0.32	
27		0.26			0.29			0.24	
28		0.53			0.57			0.55	

Note. All values measured in microvolts (μV)

Table 13. *Amplitude and Amplitude Ratios of Waves I and V at Three Intensity Levels in NH Group*

	25 dBnHL			20 dBnHL			15 dBnHL		
Ear	Wave I	Wave V	V/I Ratio	Wave I	Wave V	V/I Ratio	Wave I	Wave V	V/I Ratio
1		0.45			0.33			0.27	
2		0.26			0.21			0.14	
3		0.43			0.24			0.18	
4		0.38			0.31			0.28	
5		0.21			0.25			0.2	
6		0.26			0.22			0.23	
7		0.23			0.23			0.16	
8		0.36			0.23			0.17	
9		0.26			0.24			0.07	
10		0.26			0.22				
11		0.25			0.16			0.15	
12		0.29			0.25			0.26	
13		0.17			0.22			0.08	
14		0.48			0.41			0.35	
15		0.38			0.37			0.27	
16		0.2			0.16			0.18	
17		0.38			0.21			0.2	
18		0.42			0.28			0.21	
19		0.26			0.25			0.17	
20		0.22			0.27			0.16	
21		0.45			0.41			0.31	
22		0.24			0.22			0.11	
23		0.19			0.08				
24		0.29			0.25			0.15	
25		0.22			0.24			0.12	
26		0.33			0.31			0.21	
27		0.2			0.2			0.15	
28		0.46			0.39			0.33	

Note. All values measured in microvolts (μV)

Table 14. *Amplitude and Amplitude Ratios of Waves I and V at Two Intensity Levels in NH Group*

	25 dBnHL			20 dBnHL		
Ear	Wave I	Wave V	V/I Ratio	Wave I	Wave V	V/I Ratio
1		0.21				
2						
3		0.1				
4		0.21			0.14	
5		0.16				
6		0.24				
7		0.14			0.1	
8		0.15				
9						
10						
11		0.12				
12		0.17			0.11	
13						
14		0.29			0.2	
15		0.22				
16						
17						
18		0.19				
19		0.12				
20						
21		0.26			0.16	
22						
23						
24						
25		0.1				
26		0.22			0.07	
27		0.09				
28						

Note. All values measured in microvolts (μV)

APPENDIX G

Table 15. *Absolute Latency of Waves, I, III, and V at Three Intensity Levels in Conductive HL Group*

	80 dBnHL			70 dBnHL			60 dBnHL		
Ear	Wave I	Wave III	Wave V	Wave I	Wave III	Wave V	Wave I	Wave III	Wave V
29			7.73			7.8			7.43
30		4.3	6.2		4.97	6.58			7
31	2.33		6.3			6.68			7.5
32		3.28	6.38		3.7	6.6			7.25
33			6.83			7.68			8.1
34	2.45	4.08	5.88		4.68	6.15			6.58
35		4.58	6.25			6.9			7.8
36		3.73	6.35			6.9			7.25
37			6.43			7.73			8.15
38			6.9			7.6			8.65
39			6.6			7.15			7.45
40			6.73			7.18			7.6
41		4.38	6.4		5.33	7			7.45
42			6.9			7.2			7.78
43			6.7			7.83			8.15
44			6.15			6.65			7.23
45	2.17	4.33	6.15	2.58	4.78	6.43			6.9
46	2.28	4.33	6.13			6.35			6.75
47			7.08			7.6			8.6
48	2	4.05	5.8	2.28	4.13	6.05			6.53
49	2.2		6.13			6.63			7.18
50		4.01	6.24			6.85			7.17
51			6.58			7.08			8.23
52			6.9			7.3			7.93
53	1.85	4	6.28		4.6	6.73			7.15
54			6.28			6.73			7.18
55			6.28			6.75			7.3
56			6.43			7.1			7.38

Note. All values measured in milliseconds (ms).

Table 16. *Absolute Latency of Waves, I, III, and V at Three Intensity Levels in Conductive HL Group*

	55 dBnHL			50 dBnHL			45 dBnHL		
Ear	Wave I	Wave III	Wave V	Wave I	Wave III	Wave V	Wave I	Wave III	Wave V
29			9.28						
30			7.4			7.83			8.05
31			8.38			8.75			9.38
32			7.5			7.83			8.1
33			8.65			9.03			9.68
34			6.88			7.3			8.07
35			8.3			8.53			8.73
36			7.68			8			8.42
37			8.38			8.4			8.55
38			9.13			9.4			9.75
39			7.68			8.38			8.53
40			8.15			8.55			8.93
41			8.07			8.95			9.05
42			8.85			9.18			9.4
43			8.82			9.3			9.48
44			7.35			7.63			8.05
45			7.43			7.8			8.48
46			7.45			7.98			8.1
47			9.03			9.2			9.48
48			6.83			7.05			7.3
49			7.48			7.83			8.1
50			7.62			7.95			8.45
51			8.53			9.03			9.57
52			8.35			8.65			9.13
53			7.38			7.68			8.2
54			7.6			7.8			8.23
55			7.98			8.28			8.57
56			7.83			7.93			8.48

Note. All values measured in milliseconds (ms).

Table 17. *Absolute Latency of Waves, I, III, and V at Three Intensity Levels in Conductive HL Group*

	40 dBnHL			35 dBnHL			30 dBnHL		
Ear	Wave I	Wave III	Wave V	Wave I	Wave III	Wave V	Wave I	Wave III	Wave V
29									
30			8.43						
31			9.52			10.57			10.82
32			8.57						
33			9.95						
34			9.95			10.23			
35			9.03						
36			9.05						
37			8.75			9.2			
38			10.38			10.6			
39			9.23			9.53			10.05
40			9.48			9.95			
41			9.43			9.82			
42			9.53						
43			9.88						
44			8.2			8.38			9.6
45			9.1			9.4			
46			9.55			9.3			9.45
47			10.13			10.4			11.05
48			7.55			7.95			8.38
49			8.48			8.73			9.4
50			9						
51			10.6			10.5			
52									
53			8.65			8.82			9.1
54			8.63						
55			9.4						
56			8.65			9.15			9.48

Note. All values measured in milliseconds (ms).

Table 18. *Absolute Latency of Waves, I, III, and V at One Intensity Level in Normal Hearing Group*

	25 dBnHL		
Ear	Wave I	Wave III	Wave V
29			
30			
31			
32			
33			
34			
35			
36			
37			
38			
39			
40			
41			
42			
43			
44			
45			
46			
47			
48			8.93
49			
50			
51			
52			
53			
54			
55			
56			

Note. All values measured in milliseconds (ms).

APPENDIX H

Table 19. *Interpeak Latency of Waves I-III, III-V, and I-V at Two Intensity Levels in CHL Group*

	80 dBnHL			70 dBnHL		
Ear	I-III	III-V	I-V	I-III	III-V	I-V
1						
2		1.9			1.6	
3			3.97			
4		3.1			2.9	
5						
6	1.63	1.8	3.43		1.48	
7		1.67				
8		2.62				
9						
10						
11						
12						
13		2.03			3.52	
14						
15						
16						
17	2.15	1.83	3.98	2.2	1.65	3.85
18	2.05	1.8	3.85			
19						
20	2.05	1.75	3.8	1.85	1.92	3.78
21			3.93			
22		2.23				
23						
24						
25	2.15	2.28	4.43		2.13	
26						
27						
28						

Note. All values measured in milliseconds (ms).

APPENDIX I

Table 20. *Interaural Latency Difference of Wave V and Wave I-V at Three Stimulus Levels in CHL Group*

	80 dBnHL		70 dBnHL		60 dBnHL	
Participant	Wave V	Wave I-V	Wave V	Wave I-V	Wave V	Wave I-V
15	1.03		0.03		0.72	
16	0.05		0.07		0.23	
17	0.15	0.01	0.25		0.6	
18	0.25		0.25		0.5	
19	0.25		0.08		0.5	
20	0.08	0.37	0.1		0.05	
21	0.12		0.27		0.62	
22	0.11		0.05		0.08	
23	0.15		0.65		0.08	
24	0		0.3		0.72	
25	0.32		0.42		0.3	
26	0.45		0.45		0.42	
27	0.12		0.25		0.15	
28	0.47		0.1		0.4	

Note. All values measured in milliseconds (ms).

Table 21. *Interaural Latency Difference of Wave V and Wave I-V at Three Stimulus Levels in CHL Group*

	55 dBnHL		50 dBnHL		45 dBnHL	
Participant	Wave V	Wave I-V	Wave V	Wave I-V	Wave V	Wave I-V
15	0.46					
16	0.05		0.2		0	
17	0.95		0.95		0.9	
18	0.05		0.15		0	
19	0.38		0.17		0.2	
20	0.05		0.25		0.77	
21	0.82		0.7		8.63	
22	0.06		0.05		0.03	
23	0.15		0.63		1.02	
24	0.78		0.75		0.62	
25	0.3		0.7		0.33	
26	0.65		0.75		0.7	
27	0.09		0.67		0.48	
28	1.02		1.25		0.92	

Note. All values measured in milliseconds (ms).

Table 22. *Interaural Latency Difference of Wave V and Wave I-V at Two Stimulus Levels in CHL Group*

	40 dBnHL		35 dBnHL	
Participant	Wave V	Wave I-V	Wave V	Wave I-V
15				
16	0.23			
17	0.42		1.17	
18	0.98			
19	0.18			
20	2.4		2.28	
21	0.55			
22	0.05			
23	1.85		1.3	
24				
25	0.58		0.71	
26	0.85			
27	0.03			
28	0.88			

Note. All values measured in milliseconds (ms).

APPENDIX J

Table 23. *Amplitude and Amplitude Ratios of Waves I and V at Three Intensity Levels in CHL Group*

	80 dBnHL			70 dBnHL			60 dBnHL		
Ear	Wave I	Wave V	V/I Ratio	Wave I	Wave V	V/I Ratio	Wave I	Wave V	V/I Ratio
29		0.46			0.31			0.12	
30		0.37			0.32			0.33	
31	0.14	0.51	3.66		0.26			0.23	
32		0.51			0.38			0.39	
33		0.62			0.5			0.46	
34	0.15	0.34	2.2		0.25			0.23	
35		0.79			0.54			0.4	
36		0.4			0.29			0.29	
37		0.41			0.38			0.33	
38		0.38			0.2			0.56	
39		0.65			0.33			0.35	
40		0.66			0.37			0.24	
41		0.55			0.37			0.32	
42		0.56			0.44			0.47	
43		0.33			0.3			0.42	
44		0.37			0.35			0.33	
45	0.24	0.39	1.62	0.09	0.32	3.71		0.27	
46	0.08	0.63	7.45		0.34			0.26	
47		0.43			0.36			0.31	
48	0.34	0.62	1.81	0.17	0.43	2.54		0.43	
49	0.14	0.59	4.29		0.57			0.45	
50		0.45			0.31			0.29	
51		0.36			0.33			0.29	
52		0.29			0.33			0.37	
53	0.27	0.33	1.22		0.39			0.22	
54		0.53			0.42			0.4	
55		0.59			0.36			0.37	
56		0.68			0.62			0.32	

Note. All values measured in microvolts (μV)

Table 24. *Amplitude and Amplitude Ratios of Waves I and V at Three Intensity Levels in CHL Group*

	55 dBnHL			50 dBnHL			45 dBnHL		
Ear	Wave I	Wave V	V/I Ratio	Wave I	Wave V	V/I Ratio	Wave I	Wave V	V/I Ratio
29		0.17							
30		0.3			0.23			0.2	
31		0.25			0.3			0.24	
32		0.27			0.24			0.15	
33		0.32			0.24			0.28	
34		0.2			0.26			0.38	
35		0.24			0.15			0.12	
36		0.3			0.15			0.11	
37		0.25			0.24			0.26	
38		0.28			0.28			0.17	
39		0.28			0.2			0.15	
40		0.18			0.17			0.15	
41		0.24			0.13			0.11	
42		0.48			0.23			0.22	
43		0.3			0.21			0.17	
44		0.33			0.23			0.24	
45		0.25			0.27			0.26	
46		0.26			0.27			0.21	
47		0.21			0.25			0.17	
48		0.35			0.29			0.16	
49		0.43			0.23			0.2	
50		0.25			0.14			0.14	
51		0.23			0.16			0.13	
52		0.41			0.14			0.29	
53		0.21			0.19			0.16	
54		0.29			0.27			0.2	
55		0.24			0.18			0.07	
56		0.29			0.29			0.15	

Note. All values measured in microvolts (μV)

Table 25. *Amplitude and Amplitude Ratios of Waves I and V at Three Intensity Levels in CHL Group*

	40 dBnHL			35 dBnHL			30 dBnHL		
Ear	Wave I	Wave V	V/I Ratio	Wave I	Wave V	V/I Ratio	Wave I	Wave V	V/I Ratio
29									
30		0.15							
31		0.09			0.14			0.12	
32		0.12							
33		0.11							
34		0.21			0.09				
35		0.11							
36		0.1							
37		0.26			0.14				
38		0.19			0.13				
39		0.05			0.08			0.07	
40		0.12			0.13				
41		0.07			0.08				
42		0.16							
43		0.17							
44		0.11			0.17			0.09	
45		0.14			0.09				
46		0.1			0.09			0.09	
47		0.14			0.09			0.07	
48		0.16			0.09			0.15	
49		0.17			0.17			0.15	
50		0.12							
51		0.14			0.16				
52									
53		0.2			0.17			0.14	
54		0.11							
55		0.07							
56		0.18			0.12			0.14	

Note. All values measured in microvolts (μV)

Table 26. *Amplitude and Amplitude Ratios of Waves I and V at One Intensity Level in CHL Group*

	25 dBnHL		
Ear	Wave I	Wave V	V/I Ratio
29			
30			
31			
32			
33			
34			
35			
36			
37			
38			
39			
40			
41			
42			
43			
44			
45			
46			
47			
48		0.14	
49			
50			
51			
52			
53			
54			
55			
56			

Note. All values measured in microvolts (μV)

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Towson University, Towson, Maryland
GPA: 3.93

B.A. in Communication Science and Disorders Graduated April 2015
University of Pittsburgh, Pittsburgh, Pennsylvania
GPA: 3.65

RESEARCH EXPERIENCE

Doctoral Thesis
Spring 2017 – Spring 2018

- Development of ABR Conductive Hearing Loss 'Research Library' to use in Intelligent Hearing System's (IHS) Baby ISAO Simulator Unit
- Advisor: Dr. Peggy Korczak, Towson University

CLINICAL EXPERIENCE

Ear, Nose, & Throat, Asthma and Allergy Specialty Group (ENTAA Care) – Glen Burnie & Columbia, MD
Audiology Intern – August 2017-Present

- Comprehensive adult and pediatric hearing evaluations
- Adult and pediatric hearing aid fitting, orientation, and follow up
- Adult and pediatric amplification services
  - Assistive listening device fitting and orientation
  - Hearing aid repairs
- Otoneurologic Auditory Brainstem Response (ABR)
- Electronystagmography (ENG) and Videonystagmography (VNG) assessment
- ECochG and VEMP assessment
- Assisted with cochlear implant candidacy evaluations and mapping

Chesapeake Hearing Centers – Annapolis & Severna Park, MD
Audiology Intern – May 2017-July 2017

- Comprehensive adult and pediatric hearing evaluations
- Adult and pediatric hearing aid fitting, orientation, and follow-up
- Adult and pediatric amplification services
  - Hearing aid accessory fitting and orientation
  - Hearing aid repairs
- Pediatric otoacoustic emissions (OAE) screenings
- Videonystagmography (VNG) assessment
- Participation in audiology team meetings/seminars
- Participation in hearing aid manufacturer trainings (ReSound)
- Submit patient reports using healthcare medical database

University of Maryland Medical Center, Department of Otorhinolaryngology – HNS

Baltimore, MD
Audiology Intern – January 2017-May 2017

- Comprehensive adult and pediatric hearing evaluations
- Adult hearing aid fitting, orientation, and follow-up
    - Real Ear Measurements
    - Electroacoustic Analysis
- Adult amplification services
    - Hearing aid accessory fitting and orientation
    - Hearing aid repairs
- Otoacoustic emissions (OAE)
- Otoneurologic Auditory Brainstem Response (ABR)
- ECochG and VEMP assessment
- Rotary chair and Videonystagmography (VNG) balance assessments
- Assisted with cochlear implant candidacy evaluations and mapping
- Assisted in the Tinnitus and Hyperacusis program
    - Tinnitus and hyperacusis audiologic testing
    - Tinnitus counseling and follow-up treatment
- Attend and participate in team meetings with Otology (otolaryngology residents and physicians)

Towson University Hearing and Balance Center – Towson, MD
Student Clinician – January 2016-December 2016

- Comprehensive adult and pediatric hearing evaluations
- Adult and pediatric hearing aid fitting, orientation, and follow-up
- Otoacoustic emissions (OAE)
- Diagnostic Auditory Brainstem Response (ABR) testing
- Videonystagmography (VNG) assessments
- Rotary chair testing

RELATED WORK EXPERIENCE

Towson University Institute for Well-Being – Towson, MD
Office Assistant – August 2016-May 2017

- Scan and organize patient files/charts into Practice Perfect (electronic health records)
- Verify patient's insurance plans and benefits (BCBS, Cigna, United Health)
- Perform monthly billing for IWB Wellness Center
- Schedule and manage appointments for audiology and speech-language pathology
- Record enrollment for speech-language pathology, occupational therapy, and Hussman Center for Adults with Autism programs using Excel

Towson University Hearing and Balance Center – Towson, MD
Practice Perfect (electronic medical records) Pilot Team Member – May 2016-August 2016

- Managed patient files with new electronic medical records system (first system for TU)
- Trialed report, disposition note, and other form writing within Practice Perfect software
- Created categories to store new patient files and scan old patient files

STUDENT RELATED SERVICES

Social Relations Chair of Towson Student Academy of Audiology — May 2016 - May 2017
Audiology Volunteer at Special Olympics – Towson, MD — Summer 2016
Hearing Conservation Program at TU Hearing and Balance Center — Spring 2016
National Student Academy of Audiology — Fall 2015 – Present