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# THE EFFECT OF THE ELECTRODE PLACEMENT ON THE AUDITORY BRAINSTEM RESPONSE (ABR) ON AMPLITUDE, MORPHOLOGY, AND LATENCY

**By**

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**A thesis proposal**

**presented to the faculty of**

**Towson University**

**in partial fulfillment**

**of the requirement for the degree of**

**Doctor of Audiology**

**Department of Audiology, Speech Language Pathology and Deaf Studies**

**Towson University**
**Towson, Maryland 21252**

**May 2017**

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THESIS APPROVAL PAGE

This is to certify that the thesis prepared by Alexandra Gartner entitled The Effect of the Electrode Placement on the Auditory Brainstem Response (ABR) on Amplitude, Morphology, and Latency has been approved by the thesis committee as satisfactorily completing the thesis requirements for the degree Doctor of Audiology.

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# ACKNOWLEDGEMENTS

I would like to first thank Dr. Diana Emanuel, my thesis advisor, for her expert advice, support, and countless hours dedicated to help me complete this thesis. Your motivational pep talks helped me take on this project one small step at a time. I would also like to thank my thesis committee members, Dr. Korczak, and Dr. Smith for their extraordinary support throughout this thesis. Thank you for helping guide me through this process. Lastly, I would like to thank my parents and brother. They have been my support system, biggest fans, and motivators. Without your love, encouragement, and support I would not be where I am today. Thank you.

**Abstract**

The Effect of the Electrode Placement on the Auditory Brainstem Response (ABR) on Amplitude, Morphology, and Latency

Alexandra Gartner

An oto-neurologic Auditory Brainstem Response (ABR) was recorded on 30 adult participants, with normal hearing, from three different inverting electrode montages (front of the earlobe, back of the earlobe, mastoid). The study examined ABR results including the absolute latency of waves I, III, and V; interpeak latency values for waves I- III, III- V, and I-V; latency differences for wave V with a fast and slow click stimulus; and wave V/I amplitude ratios. Results revealed there were no significant latency and/or amplitude differences between electrode montages. There was a significant gender difference after combining all participants for a total of 60 ears. Although there was a significant gender difference, these findings were not clinically relevant, indicating there is no need for gender specific ABR normative data. As all electrode montages resulted in data within normal limits, professionals should use the inverting electrode placement that they are most comfortable with to yield the lowest impedance value. These findings were in agreement with the results of prior studies.

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## KEY TO ABBREVIATIONS

**ABR-** Auditory Brainstem Response

**AEP-** Auditory Evoked Potential

**AER-** Auditory Evoked Response

**ALR-** Auditory Late Response

**ANSD-** Auditory Neuropathy Spectrum Disorder

**ASSR-** Auditory Steady State Response

**EcochG-** Electrocochleography

**EEG-** Electroencephalogram

**FFT-** Fast Fourier Transform

**GSI-61-** Grason Stadler Instrument-61

**IHS-** Intelligent Hearing System

**IPL-** Interpeak Latency

**IRB-** Institution of Research Board

**IT5-** Interaural Latency

**MLR**- Middle Latency Response

**MMN**- Mismatch Negativity response

**PAM-** Post Auricular Muscle

**SNR**- Signal to Noise Ratio

# Chapter 1

## Introduction

Auditory evoked potentials (AEPs) are electrical changes that occur throughout the auditory system in response to sound or electrical stimuli (Burkard & Don, 2015; Hall, 2007; Picton, 2010). When an electrical response is evoked by a sound and recorded from the auditory system, this is known as an auditory evoked response (AER). This response is recorded using a variety of stimuli, recording parameters, and electrode montages. An electrode montage is the placement of the electrodes over the surface of the skull. The specific electrode montage (placement of electrodes), employed in recording the AEP is dependent on which AER is being measured (Burkard & Don, 2015; Hall, 2007; Picton, 2010).

Three primary clinical applications of AEPs are 1) to determine hearing thresholds in patients who are unable to complete standard audiometric testing; 2) to identify the presence of retrocochlear pathologies; 3) and to monitor the health of the auditory nerve during surgical intervention (Beattie & Lipp, 1990; Burkard & Don, 2015; Hall, 2007; Picton, 2010). The Auditory Brainstem Response (ABR) is one of the most frequently used AEPs in clinical settings. The ABR is one of the earliest AEPs that is measured after a stimulus is presented. There has been limited research on the advantages and disadvantages of different electrode montages that are routinely used in clinical settings for best recording ABRs. This proposal includes a literature review, which will discuss the effects of electrode montage on the amplitude, latency, and overall waveform morphology of the ABR.

# Chapter 2

# Review of Literature

## Auditory Evoked Potentials (AEPs)

AEPs are clinical tools utilized to record the electrical activity generated from a variety of locations in the auditory system. Many different types of AEPs can be recorded based on differences in timing and location of the stimulated electrical activity. The different AEPs that are recorded include: Electrocochleography (ECochG), ABR, Auditory Steady State Response (ASSR), Middle Latency Response (MLR), Auditory Late Response (ALR), P300, and Mismatch Negativity (MMN) response (Hood, 2007). Table 1 separates the different AERs in terms of the anatomical area from which the electrical activity is generated, the wave characteristics in terms of latencies and amplitude measures, and the most frequently employed electrode montages used to record these responses (Hall, 2007).

AEPs are measured through the use of electrodes placed in various locations on the scalp and head, depending on which AER is being recorded (Table 1). There is an internationally recognized system for determining where to place electrodes, known as the 10-20 system (Hall, 2007; Jasper, 1958; Jurcak, Tsuzuki, & Dan, 2007; Klem, Otto Lüders, Jasper & Elger, 1999; Picton 2010). Jasper (1958) created a universal electrode placement system with specific guidelines for electrode placement. These guidelines include: 1) placing electrodes based on specific measurements that are proportional to the size of each individual's skull shape and size, 2) locating standard electrode placements for all parts of the skull, 3) and designating the electrode labels based on the anatomical brain areas covered (Jasper, 1958; Klem et al., 1999; Silverman, 1963).

Table 1. *Auditory Evoked Responses*

| AER | Anatomy | Wave Marking | Latencies/ Amplitude | Electrode Montage |
|---|---|---|---|---|
| ECochG | Outer hair cells, inner hair cells, Auditory nerve | CM, SP, AP, N1 | N1- 1.5 ms (wave I of ABR), SP amp 0.8-1.6 µV, AP amp- 2-3.7 µV | Fpz, tiptrode, (A1, A2) |
| ABR | Auditory Nerve, Brainstem | I, III, V | Wave I- 1.5 ms, wave III- 3.5 ms, wave V- 5.5 ms | Cz, A1, A2, Fpz. |
| ASSR | Brainstem, cortex | N/A | Analyze the ASSR through FFT- shows peaks of energy at the modulation frequency used | Fpz, Cz, Nape of neck or ipsilateral mastoid |
| MLR | Auditory cortex, Sub-cortical, Thalamus, auditory radiation fibers, inferior colliculus, Reticular formation, | Na, Pa, Nb | Na- 15- 25 ms, Pa- 25-30 ms , Nb - 40- 50 ms | Cz, T3 or T5, T4 or T6 |
| ALR | Auditory cortex | N1, P2 | N1- 50 ms, P2- 100 ms | Fpz, Cz, Nape of neck, ocular electrodes* |
| P300 | Hippocampus, Auditory cortex | P3 | P3- 300 ms | Fpz, Fz, nape of neck, ocular electrodes |
| MMN | Auditory cortex | MMN | Difference waveform around 200-250 ms | Fpz, Cz or Pz, Nape of neck or nose, ocular electrodes |

*Note.* Information was summarized from Hall (2007). * Ocular electrodes refer to placement of electrodes above and below the eyes

According to the Jasper (1958) 10-20 system, electrodes should be placed at set distances over the surface of the scalp as seen in Figure 1. The different locations used for electrodes are classified using a series of uppercase letters followed by a number. This labeling system indicates locations for the electrodes along a sagittal line; sagittal lines are imaginary lines separating the body into equal left and right sides with the median line being the line straight down the middle. The uppercase letter indicates the bones of the skull (e.g., frontal, parietal, and temporal), and the letters A and M represent the earlobe and mastoid placement, respectively. Numbers are used in conjunction with the letters to indicate position off the median sagittal plane (Hall, 2007; Jasper, 1958). Electrodes located to the right of the line are indicated using even numbers, while electrodes to the left are indicated using odd numbers (Figure 1) (Hall, 2007; Jasper, 1958; Klem et al., 1999).

**EcochG.**

Once electrodes are placed, an AEP electrical response is generated by an appropriate stimulus, amplified and recorded. By latency, the first AEP is electrocochleography (EcochG). EcochGs provide an electrical response that occurs when the cochlea and auditory nerve are stimulated (Burkard & Don, 2015; Ferraro, 2003; Hall, 2007; Picton, 2010). The anatomical structures stimulated are located more caudally in the auditory system, which results in earlier measured responses occurring in the first 0 to 5 milliseconds of the onset stimuli (Ferraro & Durrant, 2006; Ferraro & Ruth, 1985; Hall, 2007; Picton, 2010; Ruth, Lambert, & Ferraro, 1998). Because these electrical responses occur after the onset of the stimuli, they are known as short latency responses. Responses generated by anatomical structures that are located in a more

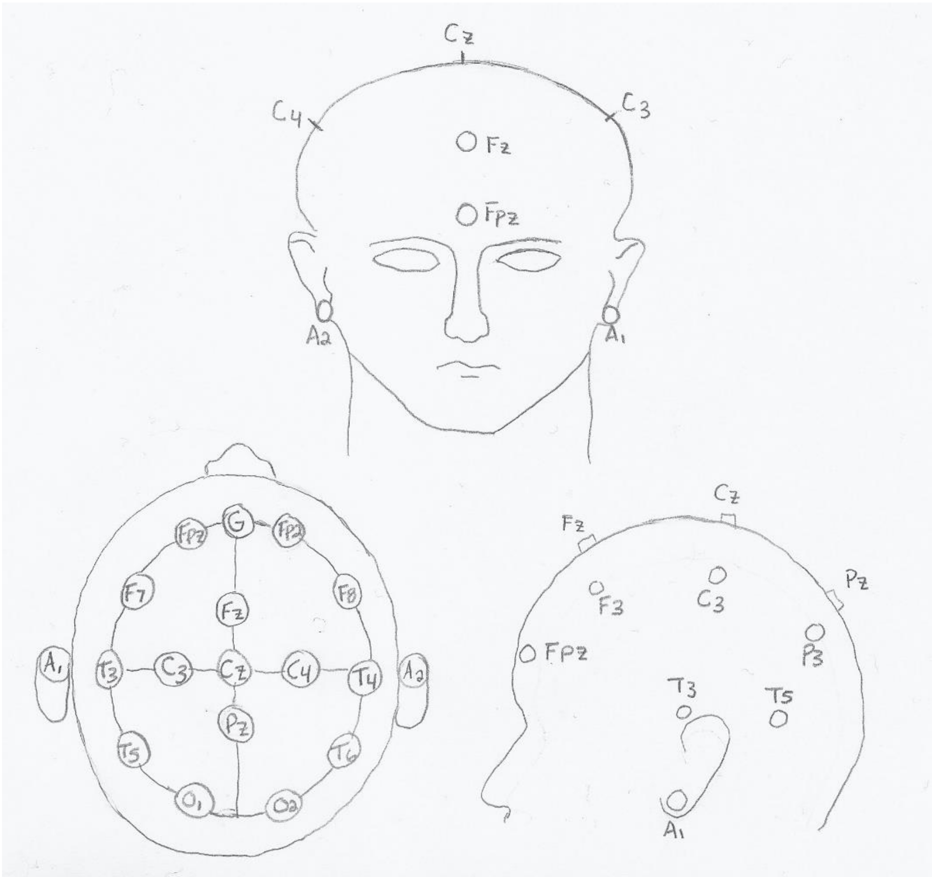


Figure 1. The 10-20 electrode positions (Jasper, 1958) as seen from the front, top and side view.

rostral position result in later latency responses. These later responses are known as late latency responses and typically occur around 50-1000 ms (Table 1).

**ABR.**

The auditory brainstem response (ABR) is considered a short latency response with responses occurring within 1 to 15 milliseconds after the onset of the stimulus (Burkard & Don, 2015; Don, Ponton, Eggermont, & Kwong, 1998; Hall, 2007; Picton, 2010). The anatomical structures that are measured with an ABR recording are the auditory nerve and brainstem structures (Hall, 2007; Picton, 2010). The ABR waves were first labeled and independently recorded by Jewett and Williston (1971). Before this time, these waves were mistaken as part of the EcochG response. When Jewett and Williston (1971) differentiated the ABR from the EcochG, they found that the absolute latencies of the various peaks were similar in adult normal hearing participants. Due to this finding, a new classification system was created using roman numerals I-VII to mark the waves (Burkard & Don, 2015; Jewett & Williston, 1971; Musiek, Gonzales, & Baran, 2015; Picton, 2010). Jewett and Williston (1971) found that when testing 12 adults with normal hearing, that all participants had detectable positive peaks and the timing and latency information was essentially the same. Since this study many other ABR studies have been completed and researchers determined that the most clinically significant waves are I, III, and V (Hall, 2007; Picton, 2010). Following the onset of a moderate to high stimulus intensity click stimulus, wave I should be present as a positive peak with an absolute latency present around 1.5 ms, wave III at 3.5 ms, and wave V at 5.5 ms (Beattie & Lipp, 1990; Burkard & Don, 2015; Hall, 2007; Jewett, Romano, & Williston, 1970; Picton 2010).

Along with the absolute latency values of each individual wave, interpeak latency values (IPL) and interaural latency differences are measured. IPL refers to the difference in ms between the ABR peaks that are recorded. The IPL values measure I-III, III-V, and I-V differentials (Hall, 2007). The values of these measurements are important for differential diagnosis of cochlear and retrocochlear dysfunction as they provide information regarding central conduction time in the peripheral and central auditory nervous system (Hall, 2007; Musiek et al., 2015). IPLs are influenced by the synchronicity of the auditory pathway, and are therefore helpful in a diagnosis of retrocochlear dysfunction. Interaural latency difference of wave V, (IT5) is a comparison of the absolute latency measures of wave V in the left and right ear to the same stimulus presented at the same stimulus intensity. If a participant has similar audiometric behavioral thresholds bilaterally, the IT5 values should have a difference of no more than 0.2 ms (Don & Kwong, 2002). If there is a difference of more than 0.2 ms, it suggests a potential retrocochlear lesion (Don & Kwong, 2002).

Another measurement that is recorded is the wave V to wave I amplitude ratio. In a normally functioning auditory system, the wave V/I amplitude ratio should be greater than 0.5 µV. If the ratio is less than 0.5 µV, it can indicate a possible retrocochlear pathology (Hall, 2007).

**Recording Parameters**

When measuring AEPs, specific recording parameters must be used to ensure optimal electrical activity is being recorded. Suggested recording parameters and stimulus parameters are listed in Table 2 (Hall, 2007). The specific parameters for ABRs are explained below.

Table 2. *Stimulus and Recording Parameters for AEPs*

| AEP | Intensity | Stimulus | Polarity | Analysis Window | Filter | Sweeps | Rate |
|---|---|---|---|---|---|---|---|
| **ECochG** | 85 dB nHL | Click or tone burst | Stimulus Dependent | 0-10 ms | 5-3000 Hz | 1000-2000 | 11.3/ sec |
| **ABR*** | 80 dB nHL | Click | Rarefaction | 10-12 ms | 100-3000 Hz | 2000 | 19.1 / sec |
| **ASSR** | Up to 120 dB nHL | Steady state signal (0.5, 1, 2, 4 kHz) | Alternating | 0-1000 ms | 1-500 Hz | Variable | N/A |
| **MLR** | 80-10 dB nHL | Click | Alternating | 0-200 ms | 10-300 Hz | 500 | 11.1 / sec |
| **ALR** | 70 dB nHL | Tone burst or speech | Rarefaction | 0-600 ms | 0.1-100 Hz | 1000 | > 1.1 / sec |
| **P300** | 70 dB nHL | Tone burst or speech | Rarefaction | 0-600 ms | 0.1- 100 Hz | 500 | > 1.1 / sec |
| **MMN** | 70 dB nHL | Tone burst or speech | Rarefaction | 0-600 ms | 0.1-30 Hz | 500 | > 1.1/ sec |

*Note.* Information was summarized from Hall (2007). * These are appropriate parameters for an oto-neurologic ABR

**Length of the post stimulus analysis window.**

The length of the post stimulus analysis window must be set appropriately to observe the desired AEPs. The analysis window length varies depending on the AEP being recorded, on the age of the participant, as well as the type of stimulus being presented. When recording an ABR in adult participants using a high intensity click stimulus, the ideal length of the post stimulus analysis window should be set to 10 to 12 ms (Hall, 2007; Hood, 2015; Picton, 2010). In ABR measurements, wave V typically occurs from 5 to 6 ms post stimulus to high intensity click stimuli (Chalak, Kalem Deshpande, & Biswas, 2013; Hall, 2007; Hood, 2015, Picton et al., 1981; Picton, 2010). However, when recording an ABR in infants, the length of the analysis window must be increased to around 15 ms as they have delayed wave V responses compared to adults (Hall, 2007; Hood, 2015; Picton et al., 1981). Infants often have a response that is at least 1 ms later than adults (Hood, 2015). When taking ABR measurements using a click stimulus for adults, the most typically used analysis window is approximately 0 to 12 ms to ensure waves I, III, and V are being recorded.

**Analog EEG/bandpass filters.**

Setting the appropriate analog EEG bandpass filters is necessary to ensure the energy present in the response is being captured. The appropriate filter setting also removes the background EEG energy from contributing to the response. When setting up the ABR recording equipment prior to measurement for an oto-neurologic ABR, the optimal frequency for the low pass filter should be set to at least 3000 Hz, with a high pass filter around 100 Hz (Hall, 2007; Hood, 2015; Picton, 2010; Suzuki, Sakabe, & Miyashita, 1982). Suzuki et al. (1982) researched the frequencies of energy that were present in an ABR. They recorded the ABR to a tonal stimuli presented at 1000, 2000, and 4000 Hz. They conducted a spectral analysis of the responses using Fast Fourier Transform (FFT) to find the primary peaks of energy in the response. Those peaks of energy occurred at 50 to 150 Hz, 500 to 600 Hz, and 1000 to 1100 Hz, with the largest energy peak occurring in the 50 to 150 Hz energy band (Suzuki et al., 1982). Suzuki et al. (1982) also determined that as stimulus intensity decreased, the energy peaks shifted to even lower frequency regions in response to all the tonal stimuli. Based on these findings it was recommended that when recording an oto-neurologic ABR to a high intensity click stimulus the recommended EEG analog bandpass filter should be set to 100 to 3000 Hz to ensure that the underlying energy present in the response is captured.

The slope of the filter also must be appropriately set to optimize the recording of the ABR. The optimal slope is ≤ 12 dB per octave. These slope values produce the least distortion to be present in the ABR waveform (Elton, Scherg, & Von Cramon, 1984). Having low distortion present in a response allows for accurate measurements of ABR waveforms with better morphology.

**Artifact rejection rate.**

Artifact rejection rate is set to reduce the amount of background EEG noise that is able to contribute to the neural response. Any signal that is outside the predetermined rejection rate is automatically rejected from the averaged responses (Sanchez & Gans, 2006). The recommended rejection level for an ABR is +/- 25 µV (Hall, 2007). This level is used because it is effective at reducing background noise while ensuring a short test time (Don & Elberling, 1994).

**Number of sweeps/ replications.**

In ABR measurements, the ongoing EEG background noise can affect the ability to accurately record neural responses even when the ABR signal is constant. To reduce the background noise without affecting the neural response of the auditory system recorded in the ABR, more sweeps or trials should be done. A trial is the amount of stimuli that is presented for one averaged waveform. Increasing the number of trial will improve the signal-to-noise ratio (SNR) so that the neural response will be larger than the background noise. The SNR that is recommended for a replicable and valid oto-neurologic ABR, is 2:1 (Hall, 2007; Picton, 2010; Picton, Linden, Hamel, & Maru, 1983). To obtain an SNR that is 2:1, it is recommended that a total of 1600 sweeps be recorded and averaged together (Picton et al., 1983). Each ABR measurement should be repeated several times to ensure that waves are repeating consistently. For each grouping of stimulus parameters, there should be two repeatable replications which will be summed together to constitute the averaged response. A replication is the number of times an averaged waveform is completed. This type of averaging process will result in a larger SNR value (Picton et al., 1983).

**Type of Stimulus.**

A click stimulus is the common stimulus used when recording oto-neurologic ABRs since it results in robust responses. A click is a brief pulse of 100 µs in duration with a spectrum of energy located between 100 to 10,000 Hz using a TDH-49 supra-aural earphone (Gorga, & Thornton, 1989). In a typical ABR, the response to a click should be recorded within 5 to 6 ms of the stimulus onset. An ABR can also be obtained with a brief tone burst rather than a click stimulus. An ABR recorded to a toneburst stimulus typically has longer latency for wave V in comparison to the response to a similar intensity click stimulus. In a toneburst stimulus, the concentration of energy present in the stimulus is located around the target frequency with some energy located above and below the target frequency known as side lobes of energy (Gorga & Thornton, 1989). Due to the concentration of energy around the target frequency, tonebursts are the stimuli of choice when recording ABRs for the purpose or estimating pure tone thresholds.

**Stimulus rate.**

Along with the type of stimulus used to elicit a response, stimulus rate is an important factor for ABR measures. Stimulus rate is important because it can affect latency and amplitude measurements as well as the morphology of the ABR response (Hood, 2015). A common stimulus rate for ABR measurement to determine a retrocochlear pathology is 20 times per second, or below. When a stimulus rate is greater than 20 stimuli per second, ABR latencies increase and the amplitude of the waves decreases (Burkard & Don, 2015; Hall, 2007; Hood, 2015; Picton et al., 1981) (Figure 2). When stimulus rate is increased from 20 clicks per second to 60 clicks per second, the amplitude of waves I and III are reduced by 50% and the amplitude at wave V is reduced by 10 to 15% (Picton et al., 1981). Increasing the stimulus rate also creates a change in the morphology of waves I and III. When stimulus rate is above 20 clicks per second, waves I and III are often unidentifiable (Hall, 2007; Picton et al., 1981) (Figure 2).

A common practice when taking ABR measurements is to increase the click rate from 20 clicks per second to 61.1 clicks per second. The use of an increased stimulus rate can indicate neurological deficits if the participant’s response latencies do not change as a function of stimulus rate (Hall, 2007; Pratt, Ben-David, Peled, Podoshin, & Scharf,

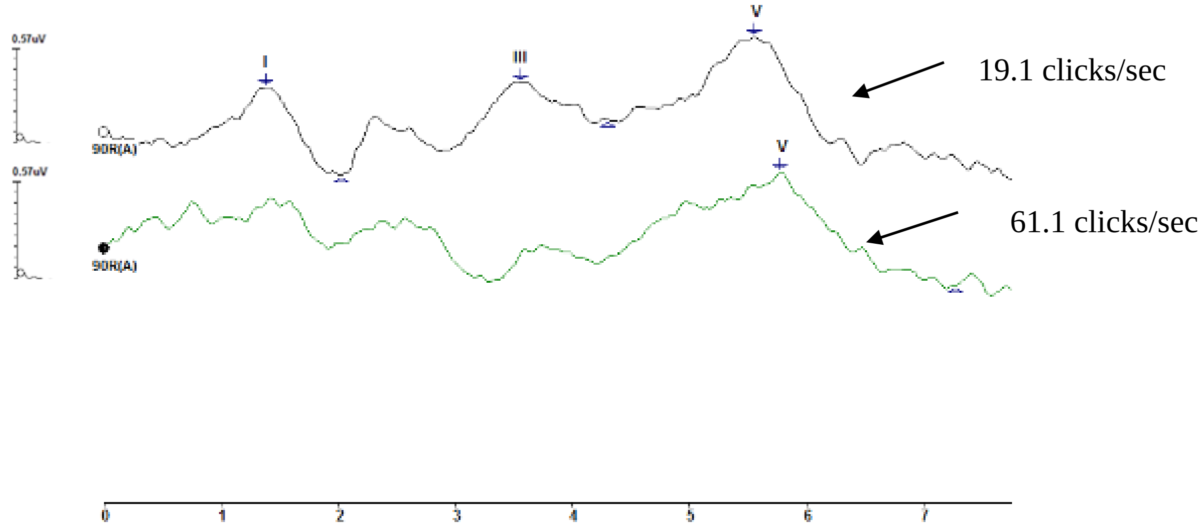


Figure 2. ABR waveforms showing the shift in latencies of waves I, III, and V as a function of increasing click rate from 19.1 clicks per second to 61.1 clicks per second. This figure also shows the degradation in overall morphology of ABR at the faster stimulus rate.  Recordings taken from pilot data.

1981). For every increase of 10 clicks per second, there should be a shift of approximately 0.1 ms in the latency of wave V (Daly, Roeser, Aung, & Daly, 1977). Therefore, when rate is increased from 19.1 clicks per second to 61.1 clicks per second, it is expected there will be a shift in the wave V latency values of approximately 0.4 ms in a typical response as seen in Figure 2.

**Stimulus polarity.**

Alternating, rarefaction, or condensation polarity click stimuli can be utilized for recording the ABR. A rarefaction click is most similar to the mechanical effects of normal cochlear physiology. A rarefaction click has an initial negative electrical pulse that results in an initial outward movement of the tympanic membrane and an upward movement of the basilar membrane, similar to how normal sound is transmitted (Coats & Martin, 1977; Hall, 2007, Hood, 2015). This movement, caused from the rarefaction click, causes an initial excitation of the hair cells. In contrast, a condensation click stimulus creates an initial positive electrical pulse resulting in an initial inward movement of the tympanic membrane and a downward movement of the basal end of the basilar membrane. This downward movement from the condensation stimulus causes an initial depolarization of the hair cells followed by excitation state milliseconds later.

Several studies have compared the effects of ABR wave latencies and amplitudes for rarefaction and condensation clicks (Borg & LO'fqvist, 1981; Coats & Martin, 1977; Hall, 2007; Picton, 2010; Stockard, Stockard, Westmoreland, & Corfits, 1978). Stockard et al. (1978) compared the effects of stimulus polarity on the ABR in normal hearing adults. The results for all participants showed a shorter wave I latency value with a rarefaction click compared to a condensation click stimulus (Figure 3). These researchers

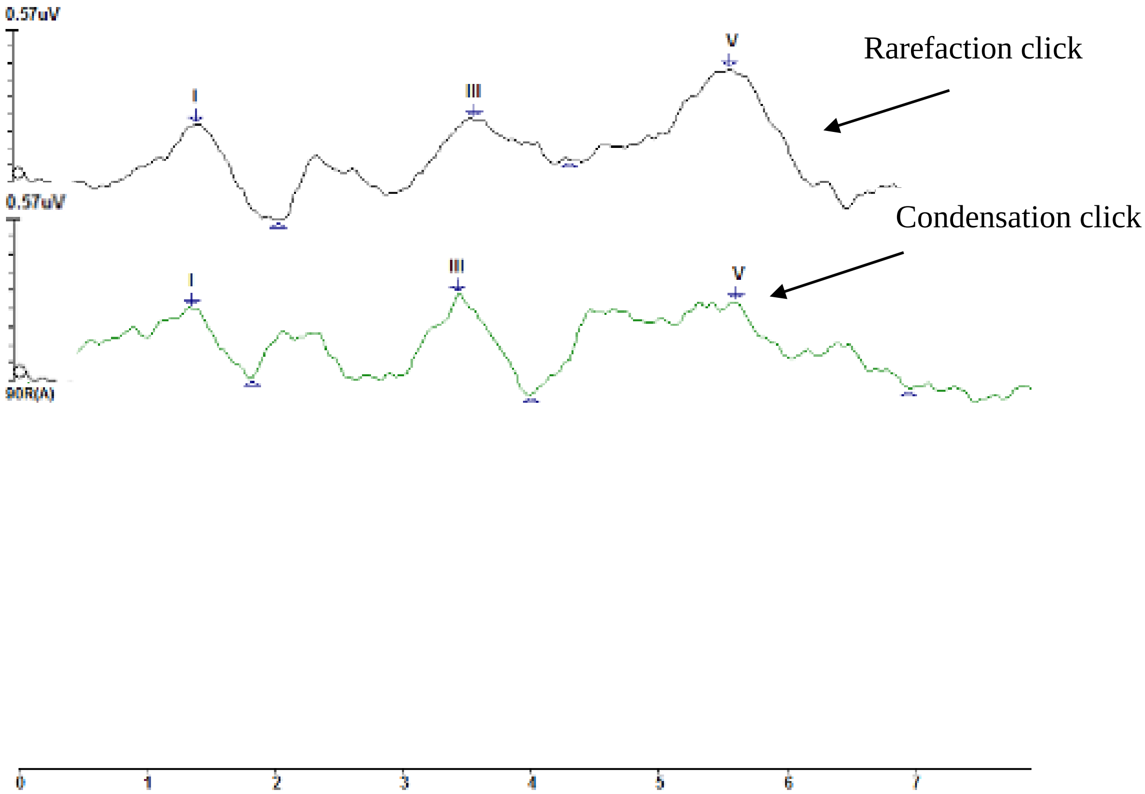


Figure 3. ABR latencies for waves I, III, and V with rarefaction and condensation clicks. Recordings taken from pilot data collected prior to this study.

also found the peak-to- peak amplitude for wave I with a rarefaction click was larger in 80% of participants when compared to wave I amplitude for a condensation click (Stockard et al., 1978). Borg and LO'fqvist (1982) had similar findings; however, they examined the effect of stimulus polarity on the latency of wave V in participants with normal hearing and hearing loss. They found a shorter wave V latency with rarefaction stimuli compared to condensation stimuli in both the examined hearing and hearing loss groups (Borg & LO'quist, 1981).

When recording oto-neurologic ABRs, both condensation and rarefaction clicks are often recorded to determine if a participant is presenting with evidence of Auditory Neuropathy Spectrum Disorder (ANSD) (Hood, 2015). When comparing rarefaction and condensation click responses for an adult with a normal functioning system, the polarity of the ABR waves should look similar. The difference in stimulus polarities can be seen in the recording of the cochlear microphonic response as it flips (inverts), or becomes the mirror image, in response to the different stimulus polarities. Specifically, in a healthy system when the response to a condensation click and a rarefaction click are summed, the cochlear microphonic response is cancelled out and ABR waves I, III, and V remain (Hood, 2015). In contrast, when comparing the ABR response from rarefaction to condensation stimuli in an adult with ANSD, the ABR waves will be inverted or absent (Berlin, Hood, Morlet, Rose, & Brashears, 2009). Therefore, summing the two responses will result in an essentially flat ABR response demonstrating that the recorded response is not a true neural response.

**Stimulus intensity.**

When recording an ABR to a click stimulus, high stimulus intensities of 70 to 90 dB nHL are recommended since they result in the most robust waves I, III, and V. When stimulus intensity is decreased, there is an increase in the latency of all the waves, a decrease in the peak to peak amplitudes, and an overall change in morphology of the waves, which results in waves that are less identifiable (Hood 2015; Picton, Hillyard, Krausz, & Galambos, 1974; Picton, Stapells, & Campbell, 1981). When stimulus intensity is decreased, often the only wave that remains observable and measurable is wave V. However, wave V is reduced in amplitude by 40% at low stimulus intensities (10-30 dB nHL) compared to wave V at the high intensities (80-90 dB nHL) (Picton et al., 1981). Wave V also has a latency shift to around 8.2 ms at 10-20 dB nHL compared to 5.5 ms found in response to a high stimulus intensity click (Picton et al., 1981). When the stimulus intensity is reduced below 50 dB nHL, waves I and III are unidentifiable, while wave V is still present (Picton et al., 1981). Wave V becomes unobservable when stimulus intensity is reduced near or below the individual's auditory threshold (Hood, 2015; Picton et al., 1974; Pratt & Sohmer, 1976).

## Electrode Montage

**Previous literature.**

As seen in Table 1, the typical electrode montage used for measuring oto-neurologic ABRs are Cz or Fz (vertex/ non-inverting or active), Fpz (ground/common), and A1 and A2, or M1 and M2 (inverting or reference) representing electrodes on the earlobes and mastoids accordingly.

The ABR is typically measured using a two-channel recording in order to record the ipsilateral and contralateral responses from click stimuli. The advantage to using a two channel recording for the ABR is that it provides more accurate information for the identification of waves. Specifically, in the ipsilateral channel, waves IV and V are often difficult to detect or separate. However, there is often a greater separation of waves IV and V in the contralateral channel. By utilizing both channels, the recorder is able to get more accurate measurements of the ABR waveforms.

Since the discovery of the ABR, studies have been performed to examine which electrode montage results in the greatest peak to peak amplitude values of the various waves, while maintaining appropriate latency values for oto-neurologic ABR recordings. The most clinically used electrode placement for recording the ABR, involves the use of an electrode placed at Fpz (ground), Cz as the noninverting lead, and A1 and A2 placement for the inverting lead (Figure 1). The test earlobe used as the inverting negative lead, is used to record the ipsilateral channel, and the non-test earlobe is used to record the contralateral recording channel. A Cz electrode placement is used more often as the noninverting lead than Fz because it results in a more robust amplitude of wave V (Beattie, Beguwala, Mills, & Boyd, 1986; Beattie & Lipp, 1990; Hall, 2007; Terkildsen & Osterhammel, 1981).

Some researchers have recommended that Fz rather than Cz should be a more frequently used electrode location for the noninverting electrode. According to Hall (2007), preparing the skin and placing the electrode at Fz is preferred because hair does not interfere with placement and tape can be used to secure the electrode into place on the skin. Also, placement at Cz is often not a viable option in some patients, including newborn infants or those who have recently had head surgery. It is difficult to be able to clean the skull well, or secure an electrode without potentially causing harm to an individual due to the sensitive nature of the skull in infants and those after surgery (Hall, 2007). Starr and Squires (1982) indicated another benefit of an Fz electrode placement is a larger wave I compared to the Cz placement. However, in clinical settings when an ABR is being used to estimate behavioral pure tone thresholds, the amplitude of wave I is not as critical as the presence of wave V.

There have been several different studies to determine which site on the scalp is the optimal electrode location for the inverting electrodes when recording the ABR. (e.g. Beattie, et al., 1986; Berlin, & Dobie, 1979; Dzulkarnain, Wilson, Bradley, & Petoe, 2008; Hall, 2007; Kevanishvilli, 1981; King, & Sininger, 1992; Pethe et al., 1998). Some of the most researched electrode site locations are the earlobes, mastoids, the 7$^{th}$ cervical vertebra (C7), and nape of the neck (Beattie, et al., 1986; Berlin, & Dobie, 1979; Dzulkarnain, Wilson, Bradley, & Petoe, 2008; Hall, 2007; Kevanishvilli, 1981; King, & Sininger, 1992; Pethe et al., 1998).

An inverting electrode placed at C7 compared to other inverting electrode placements was the focus of many research studies. When recording ABRs with an electrode placed on the 7$^{th}$ vertebra compared to electrodes on the earlobes or mastoids, there was an increase in the overall amplitude of wave V (Beattie, et al., 1986; Kevanishvilli, 1981; King, & Sininger, 1992). Since there was a larger amplitude for wave V, it was recommended that this electrode placement should be utilized for ABR threshold measures. When comparing a C7 placement to an earlobe placement, even though the electrode for C7 was placed farther away from the neural generator of the

ABR, there was no increase in the latency vales for any of the ABR waves. Kevanishvilli (1981) reported that there are two advantages to using the C7 electrode sites for the inverting electrodes. When recording using the C7 electrode, first the tester never has to switch electrodes to be able to test the other ear. Second all testing can be done with only three electrodes which leaves space around the ears free, so that supra-aural headphones can be used to present the stimuli without the possibility of interfering with electrodes Kevanishvilli, 1981).

The nape of the neck electrode placement had similar advantages to the C7 electrode placement in that this placement also only needed three electrodes and kept the ears free (Beattie et al., 1986; Kenanishvilli, 1981). Another similarity to the C7 electrode placement was that when testing the researchers found that there was an increase in the amplitude of wave V for the nape of the neck electrode compared to an earlobe or mastoid placement. There was however a decrease in the amplitude of wave I with an electrode placed on the nape of the neck (Berlin, & Dobie, 1979; Dzulkarnain, Wilson, Bradley, & Petoe, 2008; Hall, 2007; Pethe et al., 1998). One theory as to why there was an increase in the wave V amplitude for this location is that this noncephalic, or vertex to nape of neck placement, is essentially electrically silent. Electrical silence in terms of placing electrodes refers to a location that has the smallest possibility of muscle response or brain activity interfering with recordings (Neumann, Strehl, Bribaumer, & Kotchoubey, 2016). This leads to a decrease in the Post Auricular Muscle (PAM) response and any potential interference in recordings (Dzulkarnain et al., 2008; Hall, 2007; Hood, 2015; Starr & Squires, 1982; Terkildsen & Osterhammel, 1981). The PAM response is a sound evoked compound action potential that is recorded from the post

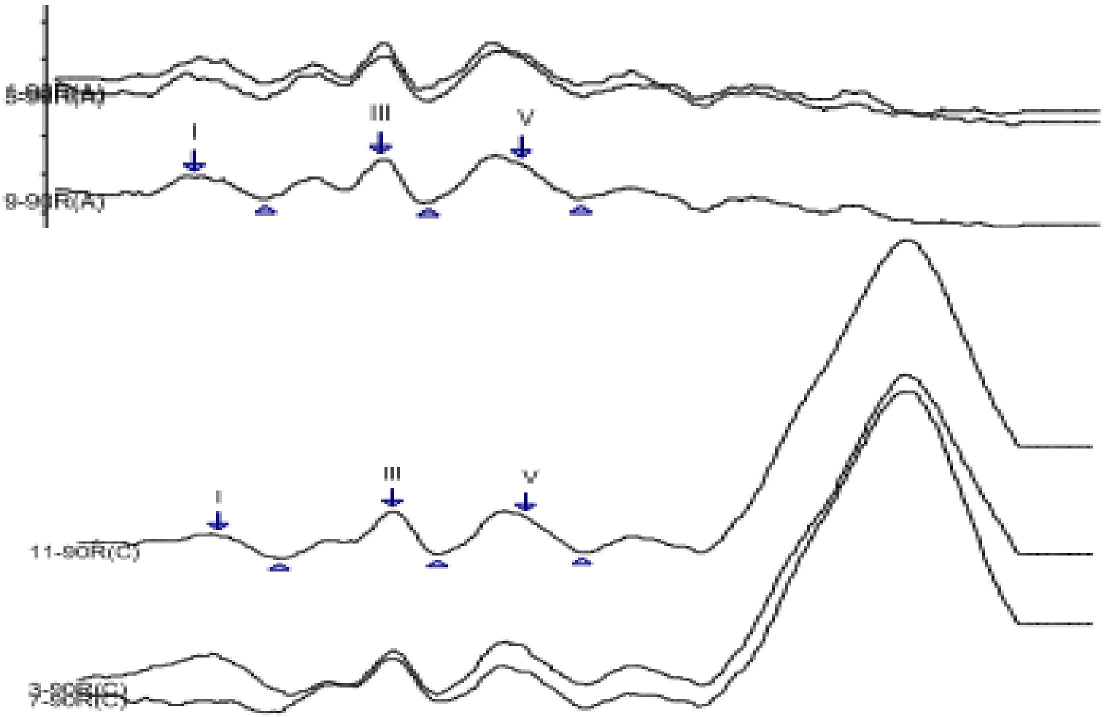


Figure 4. ABR waveforms for participant 1 in the current study, recorded from the front electrode, and mastoid electrode placement. The top marked summed waveform is from the front electrode and the bottom marked waveform from the mastoid. As can be seen in the mastoid electrode recording there is a positive reflection occurring after wave V. This is a PAM response.

auricular muscle which is located behind the pinna (Talaat, Kabel, Khalil, & Said, 2010). PAM is illustrated in Figure 4. The bottom waveform was recorded from the mastoid electrode placement and a PAM response is seen after wave V. The first waveform was recorded from the same participant from the front of the earlobe, and there is no PAM.

Although the C7 electrode as well as the nape of the neck electrode both yield a large amplitude for wave V, they are still not the most common electrode placements for the clinical use of ABRs. Clinically, it is most common for the inverting electrodes to be placed on the earlobes or mastoids. When testing using inverting electrode located on the earlobes, there is a greater amplitude found in the earlier waveforms compared to other electrode placements (Erwin, & Husain, 2015; Katbamna, Metz, Bennett, & Dokler, 1996; Pethe, Muhler, & von Specht, 1998; Terkildsen & Osterhammel, 1981). The largest amplitude measurement from an earlobe placement is wave I (Erwin, & Husain, 2015; Katbamna, Metz, Bennett, & Dokler, 1996; Pethe, Muhler, & von Specht, 1998; Terkildsen & Osterhammel, 1981). Similar results are found when electrodes are placed on the mastoids. When the inverting electrode is placed on the mastoid, there is a greater wave I amplitude across recording parameters (Berlin, & Dobie, 1979; Kavanagh & Clark, 1989; Picton 2010).

**Statement of Purpose**

The purpose of this study was to determine if there was a difference in latency and amplitude of ABR waves between three different electrode montages. This comparison study examined differences in the amplitude and latency response measurements for wave I, III, and V that resulted from electrodes placed on the front of the earlobes, back of the earlobes, and mastoids. These electrode placements were chosen as they are the most commonly used clinical montages for recording the ABR. The study examined oto-neurologic ABR results including the absolute latency of waves I, III, and V; interpeak latency values for waves I- III, III- V, and I-V; latency differences for wave V with a fast and slow click stimulus; and wave V/I amplitude ratios. The goal was to determine if one of the three electrode placement resulted in statistically or clinically significant differences in amplitude, latency, and morphology.

# Chapter 3

## Materials and Methods

The proposal for this study was reviewed by the Towson University Institutional Review Board for the Protection of Human Subjects and approved (Appendix A).

### Participants

Thirty-one volunteers with normal hearing, between the ages of 18 and 30 years were recruited to participate in the study. One participant was unable to complete the necessary testing, and their ABR recordings were not analyzed, resulting in 30 total participants. There was an attempt to recruit an equal number of male and female participants (Females 17, Males 13). Inclusion criteria for the study included: 1) pure tone thresholds that were ≤ 15 dB HL between 250-8000 Hz bilaterally, and symmetrical within 5 dB between ears, 2) normal middle ear function in each ear, and 3) present contralateral acoustic reflexes at 500, 1000, and 2000 Hz in each ear within the 90$^{th}$ percentile according to Gelfand, Schwander, and Silman (1990). Case history information was collected and participants with significant otologic history (e.g., ear surgery, history of hearing loss) were disqualified from the study. An example of the case history form and informed consent form can be found in Appendix B and C. Participants were recruited via a convenience sample, specifically direct contact with peer, students, and flyers posted around campus.

### Procedures

All testing took place in Van Bokkelen Hall on the Towson University campus in a sound treated booth. Testing took place in one session taking approximately one to two hours to complete. This session included both behavioral audiometry and oto-neurologic

ABR testing. Prior to testing, a complete case history was conducted, and when no significant history was determined, otoscopic examination, tympanometry and acoustic reflex testing was administered. Once those tests were completed, behavioral air conduction thresholds were tested at 250-8000 Hz bilaterally. Once all the inclusion criteria was met, the participants were eligible for oto-neurologic ABR testing bilaterally.

**Pure- Tone Behavioral Test Protocol**

Behavioral air conduction testing was completed using a GSI-61 audiometer and ER3A insert earphones. Air conduction testing was completed using the modified Hughson Westlake procedure using pulsed pure tone stimuli in one octave intervals from 250 to 8000 Hz in both ears. Participants were instructed to respond to tones according to the ANSI S3.21-2004 directions. Testing was completed using TDH-49 Supra Aural headphones.

**ABR Test Protocol**

Testing was completed using the Intelligent Hearing System (IHS) Smart EP program within a double walled sound treated booth in Van Bokkelen Hall. Participants were seated in a reclined chair and instructed to relax. Standard EEG disk electrodes were attached to participants using Ten20 conductive paste. All attachment areas were prepped using an alcohol wipe and Nuprep skin gel to optimize inter-electrode impedance values. Impedance values for all electrode sites were examined to ensure they were less than 5000 Ohms with inter-electrode impedance values less than 2000 Ohms. Impedance values were examined throughout testing to ensure they remained below the limits. Eight electrodes were attached with tape, using the 10-20 electrode montage system at Fpz (ground), Cz (non-inverting), A1 and A2 (front and back of earlobe), and M1 and M2 (inverting). The front of earlobe, back of earlobe, and mastoid were attached to the preamplifier on separate channels (numerically as listed) with channel four as contralateral back of earlobe. This testing configuration was determined from pilot data as described in below section.

Rarefaction clicks of 100 µs duration were presented at 90 dB nHL and a click rate of 19.1 clicks per second. These stimuli were delivered via ER3A insert earphones. Subsequently, condensation clicks with the same parameters were delivered. Then, another rarefaction test was administered with the same parameters but with a faster stimulus rate of 61.1 clicks per second. Testing in this manner was conducted for both the left and right ears, and the starting ear was randomized for all participants. An analog EEG bandpass filter set to 100 and 3000 Hz was used. The time window to record the ABR was set to a post-stimulus time of 0-12.8 ms, with an artifact rejection rate of +/- 25 µV. Each recording trial contained 1024 sweeps and had at least two replicable trials for each recording parameter and each electrode montage.

Once two replications with waveforms occurring at similar latencies were recorded for each response parameter, both replications were summed. On the summed waveforms for each test condition the following measurements were taken: 1) absolute latency values for waves I, III, and V, 2) interpeak latencies of I-III, III-V, and I-V, 3) wave V/I amplitude ratios and, 4) wave V latency values at 61.1 per second. To ensure consistency of measurements, the latency values of wave V were taken on the shoulder of wave V and the latency values for waves I and III were taken on the center of the peaks of each wave.

**Pilot Data**

Pilot data was collected on two participants to determine the best electrode montage for the preamplifier box which allowed for comparison of the location of the inverting electrodes in terms of latency, morphology, and amplitude measures. Both participants had no significant otologic case history, had clear otoscopy, present pure tone results at all test frequencies, and present contralateral reflexes bilaterally. The reason pilot data were collected was to ensure that the close electrode placements did not introduce an unusual artifact or result in abnormal latencies or morphology or large rejection rates for any of the electrode montages.

A comparison of three different test conditions was employed to determine the best method for data collection in this study (Table 3). Each participant's ABR for each independent condition was recorded using a 90 dB nHL rarefaction click stimulus presented at 19.1 clicks per second in the left ear, and repeated to ensure replicability.

For condition A, there was the ground electrode placed at Fz, the non-inverting electrode located at Cz, and the inverting electrodes were placed on the front of the earlobes. The left ear received the stimulus for the ipsilateral recording and the inverting electrode was placed on the front of the left earlobe (A1). For the contralateral recording, the inverting electrode was on the front of the right earlobe (A2). ABR amplitude and latency measurements from condition A are plotted in Table 3.1. Condition B had the ground electrode placed at Fz, the non-inverting electrode placed on Cz, and the inverting electrodes attached to the front of the earlobes, back of earlobe, and mastoid. For condition B, all electrodes on the ipsilateral side were attached to the participant, however only the ground, non-inverting, and front of the earlobe (ipsilateral and contralateral) were attached to the preamplifier box to be recorded. ABR latencies and amplitude measures for condition B are listed in Table 3.2. Condition C was the final condition tested and this used the same electrode locations as condition B. The difference was that for condition C all the electrodes were attached to the preamplifier box. When attached to the preamplifier box, channel A recorded the front of the earlobe, channel B the back of the earlobe, channel C the mastoid, and channel D recorded the contralateral front earlobe. Table 3.3 displays the ABR response measurements for both participants tested using condition C.

Results of the pilot data indicated there were only small differences in latency for waves I, III, and V and the wave I-I’ and V-V’ amplitude measures across all test conditions, similar to what would have been expected for typical test retest values of multiple ABR recordings. Artifact rejections rates between conditions were very similar with rejections values between 1 and 11. Therefore, since there were no substantial differences in ABR response measurements when testing one inverting electrode montage at a time, versus testing all the inverting electrode montages simultaneously it was decided that, condition C would be the preferred method for testing all further participants. Being able to test using condition C ensured that the patient state was the same for all inverting electrodes. This decreased any possible variability in these response measurements across electrode montages that may have been due to a change in state. This condition also reduced the test session time by two-thirds. Rather than having to record three separate ABRs per ear, this condition allowed for one ABR per ear to be recorded by utilizing multiple channels.

**Calibration**

The IHS was calibrated for stimulus intensity, linearity, and stimulus polarity prior to, and at the end of data collection. Calibration was done using a Larson Davis model 824 sound level meter and a Larson Davis model 2575 one inch microphone using a typical peak- hold calibration technique (Beattie & Rochverger, 2001).

**Statistical Analysis**

Descriptive statistics was completed separately for each different electrode montage in terms of latency values, interpeak latencies, and amplitude ratios. They included calculating the mean and standard deviation values for all measurements. Descriptive analysis, repeated measures and mixed ANOVAs were completed with an alpha level of 0.05, to compare ABR waveform differences for each electrode montage all participants, test conditions, and measured values. Once all calculations were completed, the different electrode montages were compared to determine if any one electrode montage had a significant difference in the amplitude, morphology, or latency values of the waves.

Table 3. *Pilot data for three test conditions*

Table 3.1 *Condition A latency and amplitude measures*

| Test Condition A | | |
|---|---|---|
| | Participant 1 | Participant 2 |
| Latency (ms) | Front earlobe to Cz | Front earlobe to Cz |
| Waveform | | |
| I | 1.40 | 1.50 |
| III | 3.63 | 3.75 |
| V | 5.53 | 5.80 |
| Amplitude (µV) | | |
| I-I' | 0.52 | 0.35 |
| V-V' | 1.03 | 0.47 |

Table 3.2 *Condition B latency and amplitude measures*

| Test Condition B | | |
|---|---|---|
| | Participant 1 | Participant 2 |
| Latency (ms) | Front earlobe to Cz | Front earlobe to Cz |
| Waveform | | |
| I | 1.38 | 1.45 |
| III | 3.63 | 3.73 |
| V | 5.50 | 5.85 |
| Amplitude (µV) | | |
| I-I' | 0.66 | 0.53 |
| V-V' | 1.09 | 0.41 |

Table 3.3 *Condition C latency and amplitude measures*

| Test Condition C | | | | | | |
|---|---|---|---|---|---|---|
| | Participant 1 | | | Participant 2 | | |
| Latency (ms) | Front ear to Cz | Back ear to Cz | Mastoid to Cz | Front ear to Cz | Back ear to Cz | Mastoid to Cz |
| Waveform | | | | | | |
| I | 1.40 | 1.40 | 1.35 | 1.50 | 1.5 | 1.45 |
| III | 3.58 | 3.60 | 3.55 | 3.80 | 3.78 | 3.73 |
| V | 5.53 | 5.53 | 5.53 | 5.83 | 5.88 | 5.85 |
| Amplitude (µV) | | | | | | |
| I-I' | 0.49 | 0.50 | 0.45 | 0.50 | 0.49 | 0.38 |
| V-V' | 0.97 | 0.95 | 1.20 | 0.38 | 0.38 | 0.46 |

# Chapter 4

# Results

Recall ABRs were recorded at three different electrode montages (front of the ear, back of the ear, and mastoid), for both the left and right ears, at two different click rates, and at two stimulus polarities. Rarefaction and condensation clicks were recorded for all participants. There was no inversion of waves when switching stimulus polarities indicating that ANSD was not present for any participant. Therefore, all subsequent analyses were conducted using rarefaction click data. All participants had latency measurements that were recorded within normal limits based on Towson University's ABR normative data for the HIS Smart EP system. Raw data can be found in Appendices D-H.

Descriptive statistics were compiled and repeated by ear, gender, electrode montage, and waveform measurement. Ear-specific descriptive statistics can be found in Table 4, and gender-specific statistics can be found in Table 6.

## Ear Differences

Examination of Figure 5 indicates minimal differences in the mean latencies of waves I, III, and V between right and left ears across electrode montages and waveforms. There was a characteristic and predictable increase in absolute latency from waves I to III, and waves III to V, as seen in normal ABR measurements. For all electrode montages and ABR waves, there were no distinct differences between ears. Table 4 provides mean data for absolute latencies separated by ears. Table 4 shows the largest interaural difference between ears of 0.0573 ms occurred at Wave I for the front of the

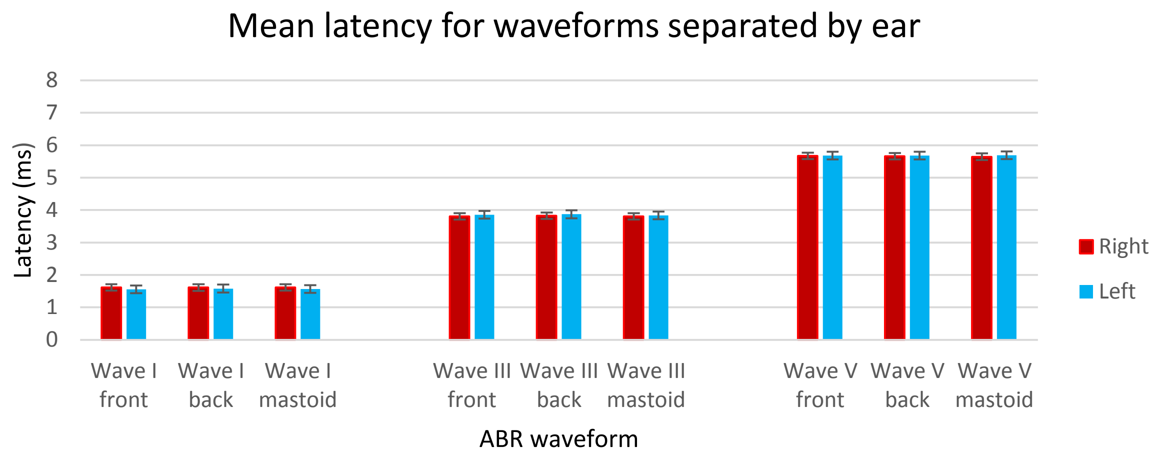


*Figure 5.* Mean latency values for the left and right ears for each waveform and electrode montage. Error bars indicate 95% confidence intervals.

Table 4

*Descriptive statistics separated by right and left ears*

| Right Ear | Mean | SD | Left Ear | Mean | SD |
|---|---|---|---|---|---|
| Absolute Latencies | | | Absolute Latencies | | |
| Wave I front | 1.6143 | .12045 | Wave I front | 1.5570 | .13414 |
| Wave I back | 1.6117 | .13435 | Wave I back | 1.5803 | .12383 |
| Wave I mastoid | 1.6163 | .14368 | Wave I mastoid | 1.5640 | .13111 |
| | | | | | |
| Wave III front | 3.8093 | .14765 | Wave III front | 3.8567 | .13270 |
| Wave III back | 3.8247 | .13746 | Wave III back | 3.8713 | .13853 |
| Wave III mastoid | 3.8097 | .16091 | Wave III mastoid | 3.8337 | .14824 |
| | | | | | |
| Wave V front | 5.6720 | .13737 | Wave V front | 5.6847 | .14522 |
| Wave V back | 5.6593 | .14460 | Wave V back | 5.6813 | .15305 |
| Wave V mastoid | 5.6460 | .14048 | Wave V mastoid | 5.6890 | .15361 |

*Note.* Mean latency and standard deviations (SD) of ABR measurements separated by right and left ears.

earlobe electrode montage, and the smallest interaural difference of 0.0127 ms occurred for waveform V for the front of the earlobe.

A 3x3x2x2 (electrode montage, waveform, gender, and ear) mixed model variance ANOVA was conducted (Tables 5.1- 5.5). Mauchly's test indicated the assumption of spericity was not violated. There were no statistically significant differences for ears, genders, or electrode montages. There was a statistically significant difference in the absolute latencies between waves I to III and waves III to V. This was expected due to the normal shift in latency that occurs between waveforms I, III, and V. This finding was present in all further analyses and will not be highlighted in further sections.

Results of the four way ANOVA indicated that there were no statistically significant differences between ears, $F(1.00, 12.00) = 2.146$, $p < 0.169$. As there were no ear differences data were collapsed for all further analyses for a total of 60 ears. There was a significant interaction that occurred between waves and ears, $F(2,24) = 6.209$, $p = 0.007$. There were no other significant interactions that occurred within variables.

**Gender Differences**

Table 6 and Figures 6 and 7 provide descriptive statistics for absolute latency values separated by gender. Examination of Table 6 indicates there were no distinct differences in latencies between genders. Figure 5 and Figure 6 indicate mean latency values were similar across electrode montage and waves for males and females. Examination of Table 6 indicates males had somewhat greater mean latencies for all montages for waves III and V. The largest mean latency difference of 0.1478 ms across

Table 5.1

*Tests of within subjects effects for waveform, montage, gender, and ear.*

| | Type III Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Waveform | 1312.819 | 2 | 656.409 | 10698.657 | .000 |
| Montage | .006 | 2 | .003 | 1.157 | .331 |
| Gender | .435 | 1 | .435 | 3.956 | .070 |
| Ear | .013 | 1 | .013 | 2.146 | .169 |

*Note.* Mauchly's test was not significant and spericity was assumed for waveforms, montages, genders, and ears.

Table 5.2

*ANOVA pairwise comparisons for waveforms.*

| (I) waveform | (J) waveform | Mean Difference (I-J) | Std. Error | Sig. | 95% Confidence Interval for Difference | |
|---|---|---|---|---|---|---|
| | | | | | Lower Bound | Upper Bound |
| I | III | -2.260 | .030 | .000* | -2.342 | -2.177 |
| | V | -4.095 | .031 | .000* | -4.181 | -4.009 |
| III | I | 2.260 | .030 | .000* | 2.177 | 2.342 |
| | III | -1.836 | .023 | .000* | -1.899 | -1.772 |
| V | I | 4.095 | .031 | .000* | 4.009 | 4.181 |
| | II | 1.836 | .023 | .000* | 1.772 | 1.899 |

*Note.* * = the mean difference is significant at the .05 level. Adjustment for multiple comparisons: Bonferroni

Table 5.3

*ANOVA pairwise comparisons for electrode montages.*

| (I) montage | (J) montage | Mean Difference (I-J) | Std. Error | Sig. | 95% Confidence Interval for Difference | |
|---|---|---|---|---|---|---|
| | | | | | Lower Bound | Upper Bound |
| Front | Back | -0.006 | .005 | .757 | -0.021 | 0.008 |
| | Mastoid | 0.002 | .006 | 1.000 | -0.016 | 0.019 |
| Back | Front | 0.006 | .005 | .757 | -0.008 | 0.021 |
| | Back | 0.008 | .006 | .442 | -0.006 | 0.022 |
| Mastoid | Front | -0.002 | .006 | 1.000 | -0.019 | 0.016 |
| | Back | -0.008 | .005 | .442 | -0.022 | 0.006 |

*Note.* Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni

Table 5.4

*ANOVA pairwise comparisons for ears*

| (I) ears | (J) ears | Mean Difference (I-J) | Std. Error | Sig. | 95% Confidence Interval for Difference | |
|---|---|---|---|---|---|---|
| | | | | | Lower Bound | Upper Bound |
| Right | Left | -.010 | .007 | .169 | -.026 | .005 |
| Left | Front | .010 | .007 | .169 | -.005 | .026 |

*Note.* Based on estimated marginal means Adjustment for multiple comparisons: Bonferroni.

Table 5.5

*ANOVA pairwise comparisons for gender.*

| (I) ears | (J) ears | Mean Difference (I-J) | Std. Error | Sig. | 95% Confidence Interval for Difference | |
|---|---|---|---|---|---|---|
| | | | | | Lower Bound | Upper Bound |
| Female | Male | -.061 | .031 | .070 | -.128 | .006 |
| Male | Female | .061 | .031 | .070 | -.006 | .128 |

*Note.* Based on estimated marginal means Adjustment for multiple comparisons: Bonferroni.

Table 6

*Descriptive statistics separated by gender*

| Gender: Female | Mean | SD | Variance | Gender: Male | Mean | SD | Variance |
|---|---|---|---|---|---|---|---|
| Absolute Latencies | | | | Absolute Latencies | | | |
| Wave I front | 1.5735 | .11162 | .012 | Wave I front | 1.6015 | .15088 | .023 |
| Wave I back | 1.5841 | .11797 | .014 | Wave I back | 1.6115 | .14318 | .021 |
| Wave I mastoid | 1.5885 | .12524 | .016 | Wave I mastoid | 1.5923 | .15754 | .025 |
| Wave III front | 3.7850 | .14387 | .021 | Wave III front | 3.8958 | .11183 | .013 |
| Wave III back | 3.8047 | .13916 | .019 | Wave III back | 3.9046 | .11850 | .014 |
| Wave III mastoid | 3.7576 | .14321 | .021 | Wave III mastoid | 3.9054 | .12625 | .016 |
| Wave V front | 5.6432 | .14520 | .021 | Wave V front | 5.7242 | .12146 | .015 |
| Wave V back | 5.6288 | .15235 | .023 | Wave V back | 5.7246 | .12520 | .016 |
| Wave V mastoid | 5.6221 | .15845 | .025 | Wave V mastoid | 5.7269 | .10840 | .012 |

*Note.* Mean latency values for males and females of all participants tested. SD= standard deviation.

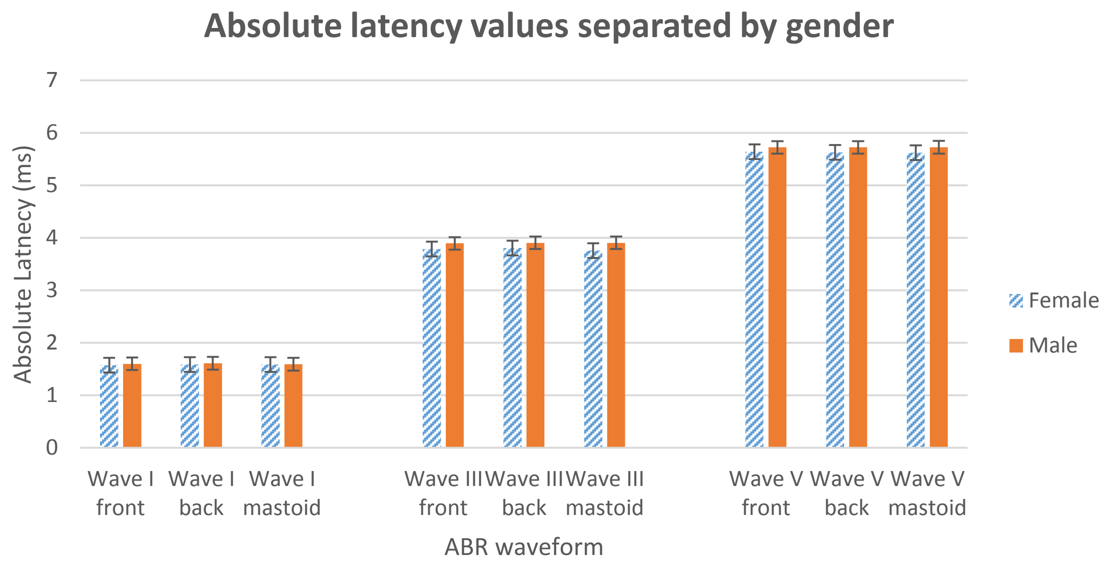


*Figure 6.* Mean absolute latency values separated by gender. As can be visualized there are slight variations between genders, with male mean latency values occurring later than females.

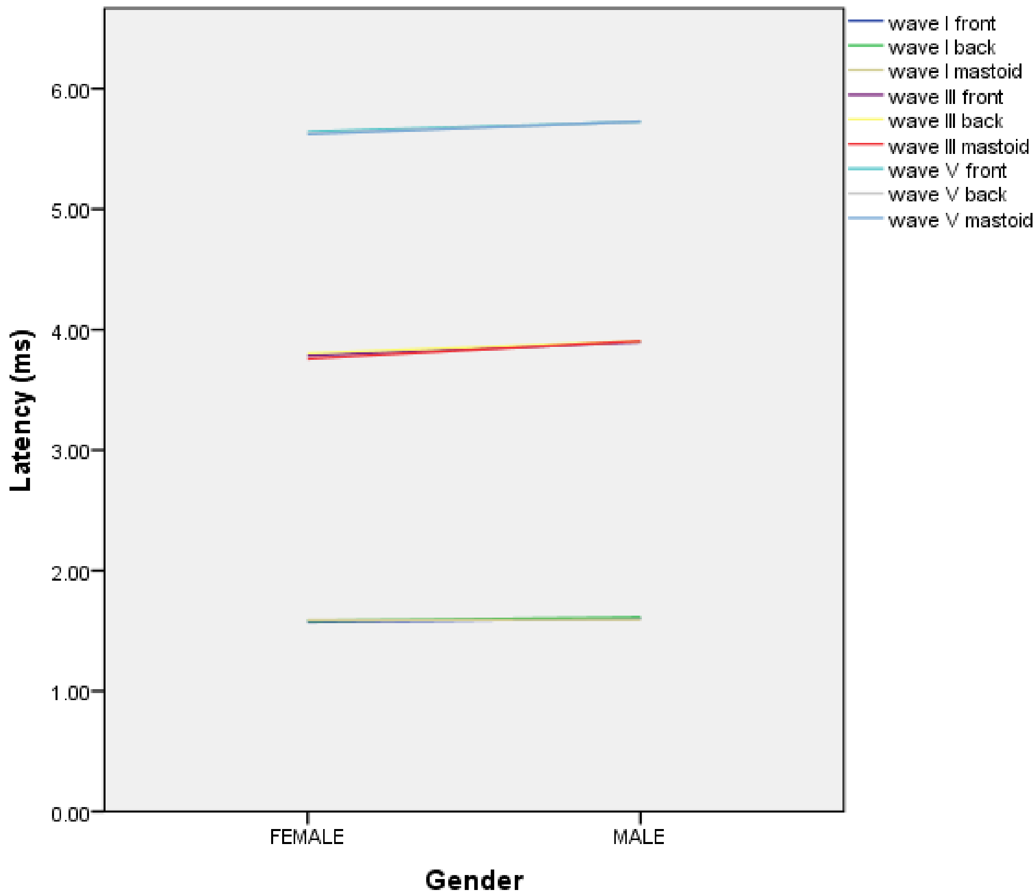


*Figure 7.* Represents the gender differences between waveforms and montages.

gender occurred for Wave III using the mastoid electrode montage, and the smallest difference of 0.0038 ms occurred for wave I using the mastoid placement.

A 3x3x2 (montage, waveform, and gender) mixed model ANOVA was conducted. Mauchly's test indicated the assumption of sphericity was not violated for any condition. The ANOVA indicated significant main effects for gender as seen in Tables 7.1 and 7.2. There were no significant differences between electrode montages in all conditions as seen in Table 7.3. There was a significant interaction between waveform and gender, $F(2,50) = 6.352$, $p = 0.003$. There were no other significant interactions between other variables.

Gender differences were plotted based on electrode montage to further examine the difference between genders. As can be examined in Figure 7, there appear to be three lines. However, it is actually nine lines representing each electrode montage at each waveform. They are very similar in value and appear stacked. For a clearer look at the differences between genders for specific electrode montage and waveform, Figures 8.1 to 8.3 are provided. As examined in Figure 8.1, for wave I, there were slight differences between genders. The line is almost parallel to the x-axis indicating values are similar. However, visualized in Figures 8.2 and 8.3 there were greater inclines of the lines and more variability between genders for waveforms III and V. The largest difference between genders appeared to be for waveform III with the mastoid electrode placement. This corresponds with the greatest difference between waveforms as noted above. The gender lines for waveform III and V were not parallel to the x-axis, and supported the finding that there were statistically significant differences between genders for waveform

Table 7.1

*Test of within subject effects*.

| Source | Type III Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Waveform | 1307.140 | 2 | 653.570 | 14370.544 | .000* |
| Montage | .006 | 2 | .003 | 1.392 | .258 |
| Gender | .629 | 1 | .629 | 8.375 | .008* |

*Note*. Mauchly's test was not violated and sphericity is assumed. * = significant differences.

Table 7.2

*ANOVA pairwise comparisons for gender differences*

| | | Mean Difference | | | 95% Confidence Interval for Difference | |
|---|---|---|---|---|---|---|
| (I) Gender | (J) Gender | (I-J) | Std. Error | Sig. | Lower Bound | Upper Bound |
| Female | Male | -.073 | .025 | .008* | -.126 | -.021 |
| Male | Female | .073 | .025 | .008* | .021 | .126 |

*Note*. *= The mean difference is significant at the .05 level.

Table 7.3

*ANOVA pairwise comparisons for electrode montages.*

| | | Mean Difference | | | 95% Confidence Interval for Difference | |
|---|---|---|---|---|---|---|
| (I) montage | (J) montage | (I-J) | Std. Error | Sig. | Lower Bound | Upper Bound |
| Front | Back | -.005 | .005 | .906 | -.017 | .007 |
| | Mastoid | .004 | .006 | 1.000 | -.012 | .020 |
| Back | Front | .005 | .005 | .906 | -.007 | .017 |
| | Mastoid | .009 | .005 | .221 | -.003 | .021 |
| Mastoid | Front | -.004 | .006 | 1.000 | -.020 | .012 |
| | Back | -.009 | .005 | .221 | -.021 | .003 |

*Note*. Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni.

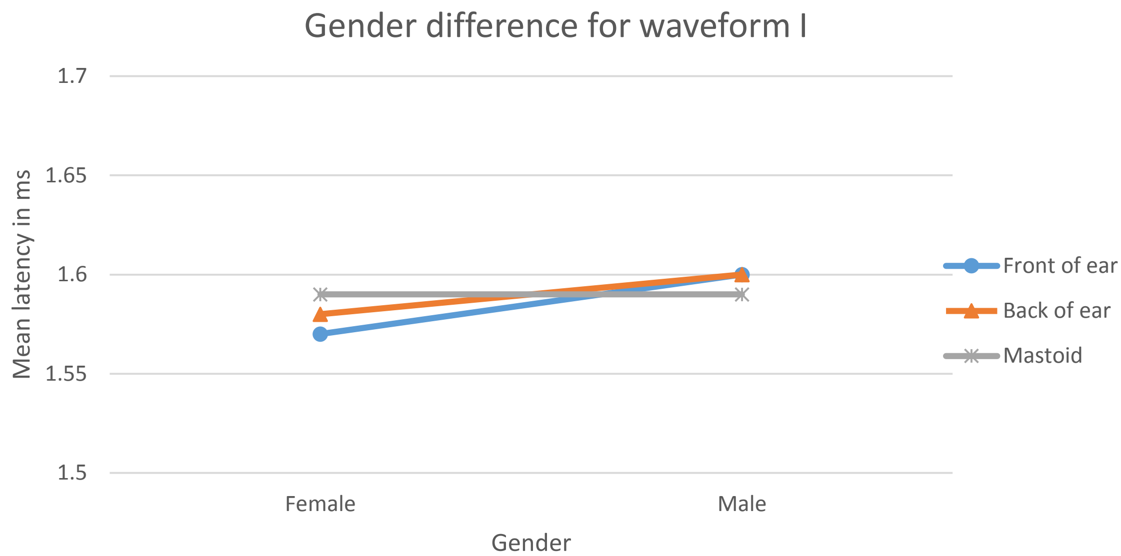


*Figure 8.1.* Gender differences for waveform I and three electrode montages.

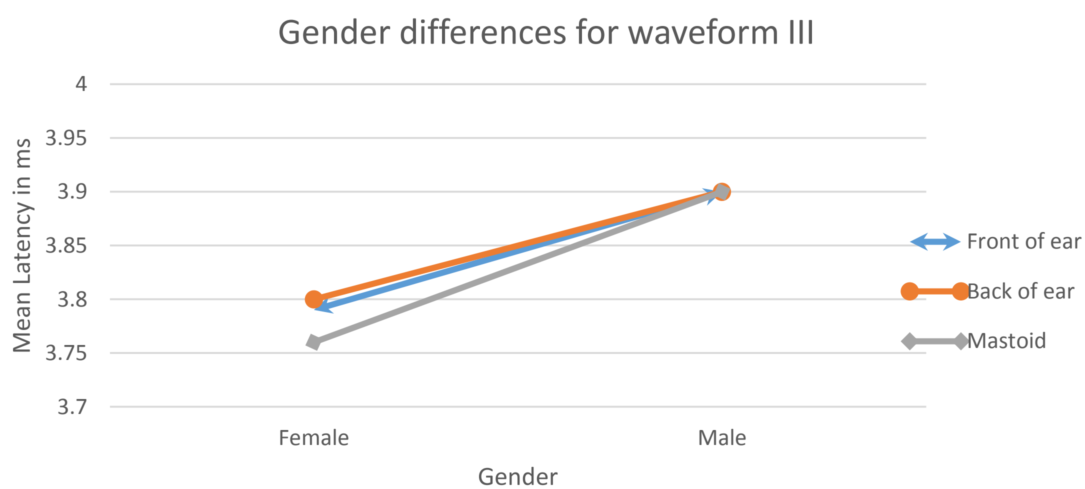


*Figure 8.2.* Gender differences for waveform III and three electrode montages.

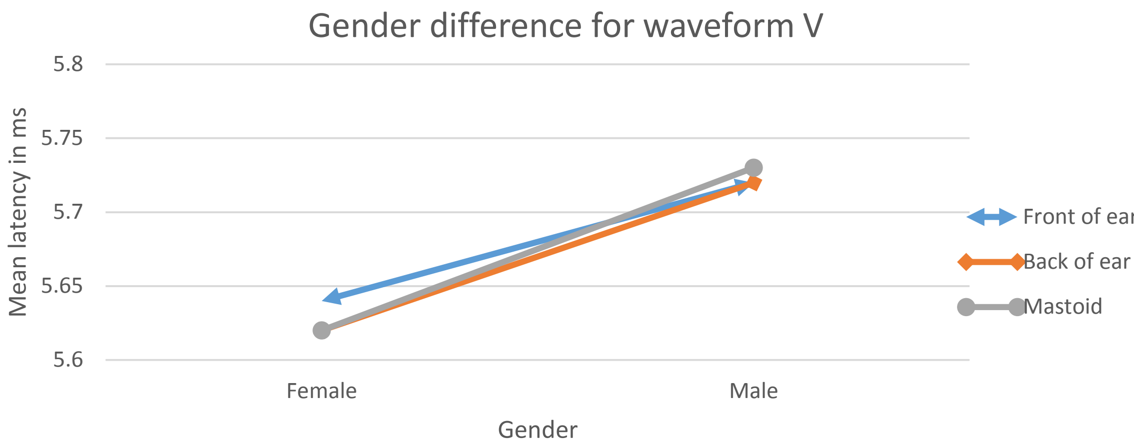


*Figure 8.3.* Gender differences for waveform V and three electrode montages.

III and V. In Figures 8.1-8.3 the lines are crossing. This supports the above finding that there were significant interactions for waveform and gender.

Since there were statistically significant differences between genders, further analyses were completed on pure tone audiometric data. Upon looking at audiometric data, there were no significant differences between thresholds of males and females for the left and right ears; all were within normal limits (≤15 dB). Mean threshold data can be examined in Table 8 and Figure 9.

A 6x2 (pure tone frequency and gender) mixed ANOVA was calculated. Mauchly's test indicated the assumption of sphericity was not violated. There were no statistically significant differences in pure tone thresholds between genders. There was a statistically significant differences between pure tone thresholds 2000 Hz and 4000 Hz as seen in Table 9. The results at all other test frequencies were not statistically significant.

**Electrode Montage Differences**

Table 10 and Figure 10 display latency information collapsed by ear for waveforms I, III, and V for all electrode montages. Descriptive statistics for all ears separated by electrode montage and waveform can be examined in Table 10. Visual representation of the descriptive statistics can be examined in Figure 9. Table 10 shows the largest difference of 0.263 ms within waveforms occurred at Wave III between the back of earlobe and mastoid electrode montage, and the smallest difference of 0.006 ms at waveform I between the back of the earlobe and mastoid placement.

A 3x2x2 ANOVA calculated by electrode montages, genders, and waveforms was analyzed. Results of this model indicated that there were no significant differences

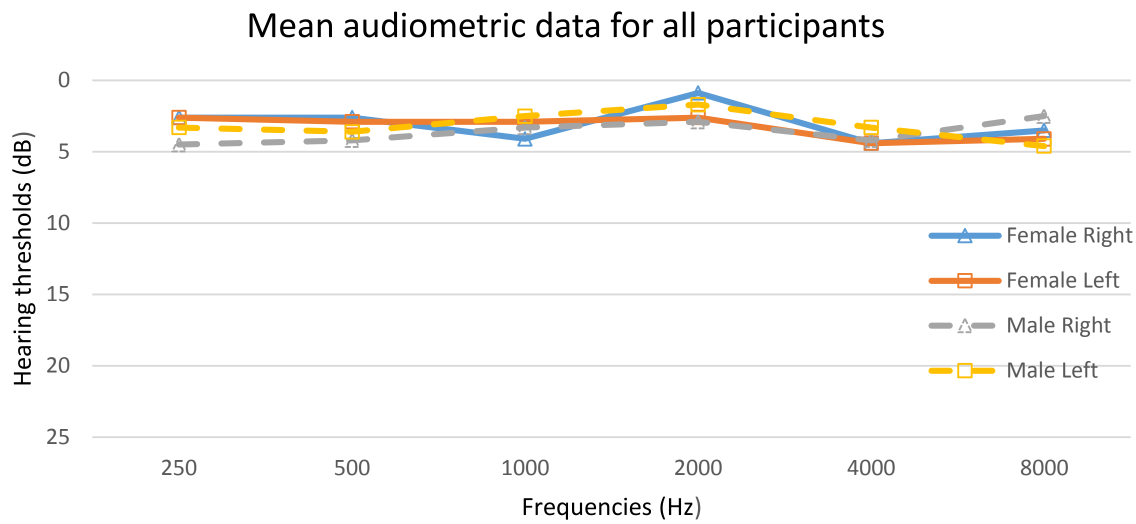


*Figure 9*. Mean audiometry data for males and females for both right and left ears.

Table 8

*Mean audiometry data for all participants separated by gender and ear*

| | Female | | Male | |
|---|---|---|---|---|
| Frequencies (Hz) | Right (dB) | Left (dB) | Right (dB) | Left (dB) |
| 250 | 2.6 | 2.6 | 4.5 | 3.3 |
| 500 | 2.6 | 2.9 | 4.2 | 3.6 |
| 1000 | 4.1 | 2.9 | 3.3 | 2.5 |
| 2000 | 0.88 | 2.6 | 2.9 | 1.7 |
| 4000 | 4.4 | 4.4 | 4.2 | 3.3 |
| 8000 | 3.5 | 4.1 | 2.5 | 4.6 |

*Note.* Average of all audiometric data between genders. There are not significant differences between genders in terms of pure tone audiometry. All thresholds are within normal limits of hearing.

Table 9

*ANOVA pairwise comparisons for frequency.*

| (I) frequency (Hz) | (J) frequency (Hz) | Mean Difference (I-J) | Std. Error | Sig. | 95% Confidence Interval for Difference Lower Bound | Upper Bound |
|---|---|---|---|---|---|---|
| 250 | 500 | 3.331E-16 | .439 | 1.000 | -1.423 | 1.423 |
| | 1000 | .096 | .563 | 1.000 | -1.730 | 1.923 |
| | 2000 | 1.154 | .624 | 1.000 | -.870 | 3.177 |
| | 4000 | -.865 | .604 | 1.000 | -2.823 | 1.093 |
| | 8000 | -.769 | .568 | 1.000 | -2.612 | 1.073 |
| 500 | 250 | -3.331E-16 | .439 | 1.000 | -1.423 | 1.423 |
| | 1000 | .096 | .643 | 1.000 | -1.989 | 2.181 |
| | 2000 | 1.154 | .576 | .839 | -.714 | 3.021 |
| | 4000 | -.865 | .554 | 1.000 | -2.662 | .931 |
| | 8000 | -.769 | .617 | 1.000 | -2.770 | 1.231 |
| 1000 | 250 | -.096 | .563 | 1.000 | -1.923 | 1.730 |
| | 500 | -.096 | .643 | 1.000 | -2.181 | 1.989 |
| | 2000 | 1.058 | .638 | 1.000 | -1.012 | 3.128 |
| | 4000 | -.962 | .573 | 1.000 | -2.821 | .898 |
| | 8000 | -.865 | .619 | 1.000 | -2.874 | 1.144 |
| 2000 | 250 | -1.154 | .624 | 1.000 | -3.177 | .870 |
| | 500 | -1.154 | .576 | .839 | -3.021 | .714 |
| | 1000 | -1.058 | .638 | 1.000 | -3.128 | 1.012 |
| | 4000 | -2.019 | .481 | .004* | -3.579 | -.459 |
| | 8000 | -1.923 | .609 | .062 | -3.900 | .054 |
| 4000 | 250 | .865 | .604 | 1.000 | -1.093 | 2.823 |
| | 500 | .865 | .554 | 1.000 | -.931 | 2.662 |
| | 1000 | .962 | .573 | 1.000 | -.898 | 2.821 |
| | 2000 | 2.019 | .481 | .004* | .459 | 3.579 |
| | 8000 | .096 | .490 | 1.000 | -1.493 | 1.686 |
| 8000 | 250 | .769 | .568 | 1.000 | -1.073 | 2.612 |
| | 500 | .769 | .617 | 1.000 | -1.231 | 2.770 |
| | 1000 | .865 | .619 | 1.000 | -1.144 | 2.874 |
| | 2000 | 1.923 | .609 | .062 | -.054 | 3.900 |
| | 4000 | -.096 | .490 | 1.000 | -1.686 | 1.493 |

*Note.* *= The mean difference is significant at the .05 level. Adjustment for multiple comparisons: Bonferroni

Table 10

*Descriptive statistics for the absolute latency values of waves I, III, and V for three electrode montages (n=60)*

| | Mean | SD | Variance | Min | Max | Range |
|---|---|---|---|---|---|---|
| Absolute Latencies | | | | | | |
| Wave I front | 1.5857 | .12966 | .017 | 1.23 | 1.88 | .65 |
| Wave I back | 1.5960 | .12907 | .017 | 1.33 | 1.88 | .55 |
| Wave I mastoid | 1.5902 | .13890 | .019 | 1.25 | 1.90 | .65 |
| | | | | | | |
| Wave III front | 3.8330 | .14121 | .020 | 3.50 | 4.10 | .60 |
| Wave III back | 3.8480 | .13883 | .019 | 3.58 | 4.18 | .60 |
| Wave III mastoid | 3.8217 | .15387 | .024 | 3.48 | 4.20 | .72 |
| | | | | | | |
| Wave V front | 5.6783 | .14029 | .020 | 5.35 | 5.90 | .55 |
| Wave V back | 5.6703 | .14804 | .022 | 5.30 | 5.90 | .60 |
| Wave V mastoid | 5.6675 | .14754 | .022 | 5.30 | 5.93 | .63 |

*Note*. Mean absolute latency values for three recording montages and three waveforms.

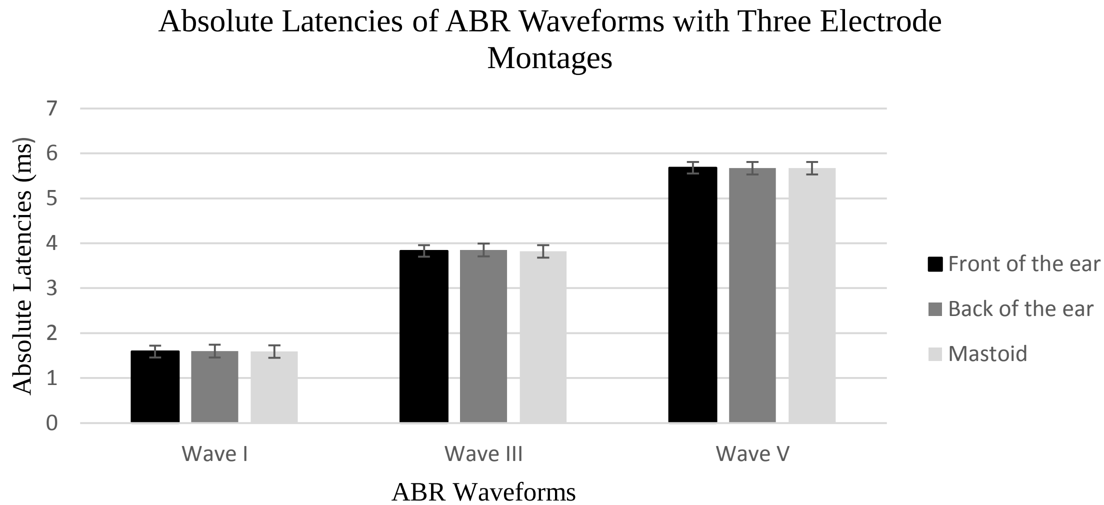


*Figure 10.* Mean latency values for waveforms I, III, V for three electrode montages.

Table 11

*Descriptive statistics for the mean interpeak latency values of I-III, III-V, I-V for three electrode montages (n=60)*

| | Mean | SD | Variance | Min | Max | Range |
|---|---|---|---|---|---|---|
| Interpeak latency | | | | | | |
| I-III front | 2.2487 | .17542 | .031 | 1.95 | 2.67 | .72 |
| I-III Back | 2.2537 | .17432 | .030 | 1.85 | 2.67 | .82 |
| I-III Mastoid | 2.2350 | .18478 | .034 | 1.85 | 2.60 | .75 |
| | | | | | | |
| III-V Front | 1.8462 | .12577 | .016 | 1.55 | 2.08 | .53 |
| III-V Back | 1.8233 | .13416 | .018 | 1.55 | 2.08 | .53 |
| III-V Mastoid | 1.8413 | .13103 | .017 | 1.57 | 2.15 | .58 |
| | | | | | | |
| I-V Front | 4.0957 | .17073 | .029 | 3.70 | 4.55 | .85 |
| I-V Back | 4.0762 | .18106 | .033 | 3.60 | 4.48 | .88 |
| I-V Mastoid | 4.0748 | .19258 | .037 | 3.60 | 4.47 | .87 |

*Note.* Mean interpeak latency values separated by montage and interpeak latency.

between electrode montages at each waveform. $F(4, 224) = 1.126$, $p = 0.345$. There were no statistically significant interactions between variables.

**Interpeak Latency Values**

Interpeak latencies were measured at I-III, III-V, and I-V for all participants. Descriptive statistics for the mean values of these latencies can be visualized in Table 11**.** Mean latencies values can also be examined in Figure 11. Table 11 shows that largest differences of 0.023 ms occurred at III-V, between the front of the earlobe and back of earlobe electrode montage, and the smallest differences of 0.0187 ms occurred at interpeak latencies of I-III between the back of the earlobe and mastoid electrode position. For individual participant information on interpeak latency values for I-III, III-V, and I-V refer to Appendix E.

A 3x3x2 (interpeak latency value, montage, and gender) mixed model ANOVA was conducted. Mauchly's test indicated that the assumption of sphericity had been violated for interpeak latency. Therefore, Greenhouse Geissser corrected tests are reported. There were statistically significant differences between interpeak latencies I-III to III-V, and III-V to I-V due to expected latency differences between interpeak measurements as seen in Tables 12.1-12.3. There were no statistically significant differences between interpeak latency values, genders, or montages, $F(4,100) = 2.120$, $p = 0.84$. There was a significant interaction between interpeak latency value and gender, $F(1.280, 32) = 8.576$, $p = 0.004$. There were no other significant interactions between variables.

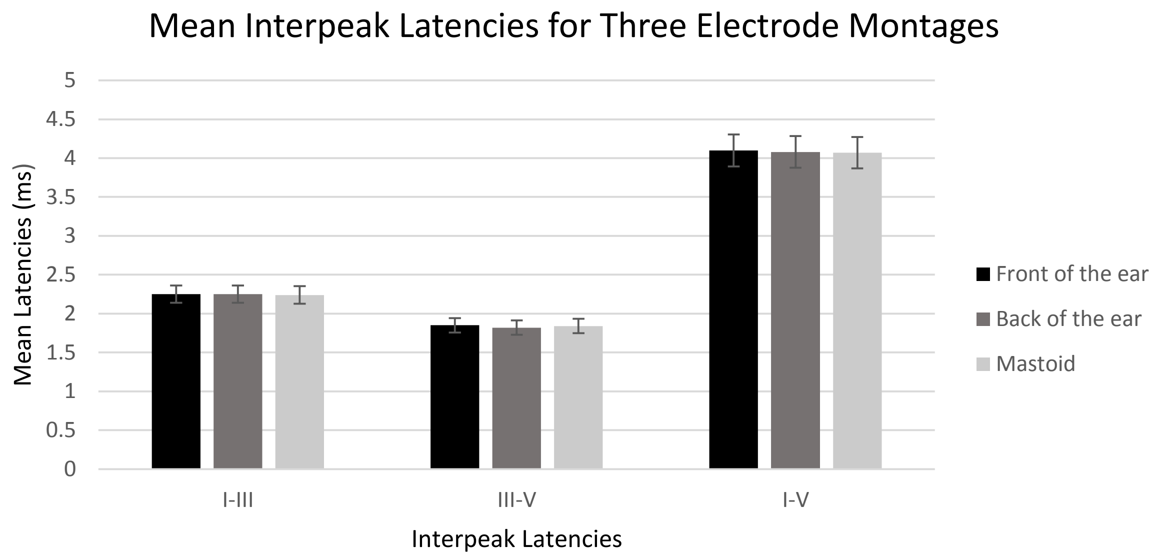


*Figure 11.* Mean interpeak latency values were separated by I-III, III-V, and I-V (n= 60). Black bars represent the front of the ear electrode placement, dark grey represents the back of the ear placement, and light grey represents a mastoid placement. Error bars indicate a 95% confidence interval.

Table 12.1

*ANOVA pairwise comparisons for interpeak latency values.*

| (I) waveforms | (J) waveforms | Mean Difference (I-J) | Std. Error | Sig. | 95% Confidence Interval for Difference Lower Bound | Upper Bound |
|---|---|---|---|---|---|---|
| I-III | III-V | .395 | .035 | .000* | .305 | .486 |
| | I-V | -1.846 | .018 | .000* | -1.893 | -1.800 |
| III-V | I-III | -.395 | .035 | .000* | -.486 | -.305 |
| | I-V | -2.242 | .026 | .000* | -2.308 | -2.175 |
| I-V | I-III | 1.846 | .018 | .000* | 1.800 | 1.893 |
| | I-V | 2.242 | .026 | .000* | 2.175 | 2.308 |

*Note*. * = The mean difference is significant at the .05 level. Adjustment for multiple comparisons: Bonferroni.

Table 12.2

*ANOVA pairwise comparisons for electrode montage.*

| (I) montages | (J) montages | Mean Difference (I-J) | Std. Error | Sig. | 95% Confidence Interval for Difference Lower Bound | Upper Bound |
|---|---|---|---|---|---|---|
| Front | Back | .012 | .008 | .498 | -.010 | .034 |
| | Mastoid | .014 | .012 | .749 | -.016 | .044 |
| Back | Front | -.012 | .008 | .498 | -.034 | .010 |
| | Mastoid | .002 | .010 | 1.000 | -.025 | .029 |
| Mastoid | Front | -.014 | .012 | .749 | -.044 | .016 |
| | Back | -.002 | .010 | 1.000 | -.029 | .025 |

*Note*. Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni.

Table 12.3

*ANOVA pairwise comparisons for gender.*

| (I) gender | (J) gender | Mean Difference (I-J) | Std. Error | Sig. | 95% Confidence Interval for Difference Lower Bound | Upper Bound |
|---|---|---|---|---|---|---|
| Female | Male | -.050 | .025 | .054 | -.102 | .001 |
| Male | Female | .050 | .025 | .054 | -.001 | .102 |

*Note*. Based on estimated marginal means Adjustment for multiple comparisons: Bonferroni.

Table 13

*Descriptive Statistics for V/I amplitude ratio in µV (n=60)*

| | Mean | SD | Variance | Min | Max |
|---|---|---|---|---|---|
| V/I ratio Front | 1.5565 | .73974 | .547 | .34 | 3.13 |
| V/I ratio Back | 1.5440 | .79239 | .628 | .46 | 4.14 |
| V/I ratio Mastoid | 1.7985 | .67363 | .454 | .47 | 3.45 |

*Note*. Mean amplitude ratio for V/I for three electrode montages.

**Peak-to-Peak Amplitude Ratio**

Wave V/I amplitude ratio was calculated for each individual for each electrode montage. Amplitude data were averaged for all montages and are provided in Table 13**.** For a normal ABR, amplitude ratios must be above 0.5 µV. All participants in this study had an amplitude ratio that was larger than that criterion, indicating there were no neurological concerns. Mean data were also well above this 0.5 µV value. Examination of individualized amplitude ratios for all participants can be found in Appendix F**.**

The largest difference of 0.2545 µV occurred between the back of the earlobe placement and mastoid placement. The smallest difference of 0.0125 µV occurred between the front of the earlobe and back of the earlobe electrode placement. These differences are shown in Figure 12. In Figure 12, the bold line indicates the cut off values for normal amplitude values at 0.5 µV. As can be seen, the mean amplitude measure of all electrode montages were all above this reference line indicating normal amplitude ratio.

A 3x2 (electrode montage and gender) mixed ANOVA was completed. Mauchly's test indicated that the assumption of sphericity had been violated for amplitude ratio between montages, therefore Greenhouse Geisser corrected tests were reported. Mauchly's test indicated that the assumption of sphericity had not been violated for gender and sphericity is assumed. Results of the ANOVA indicated there were no statistically significant differences for electrode montages or gender, $F(2,50)= .962$, $p = 0.389$ (Tables 14.1-14.3). There was no interaction that occurred between electrode montage and gender.

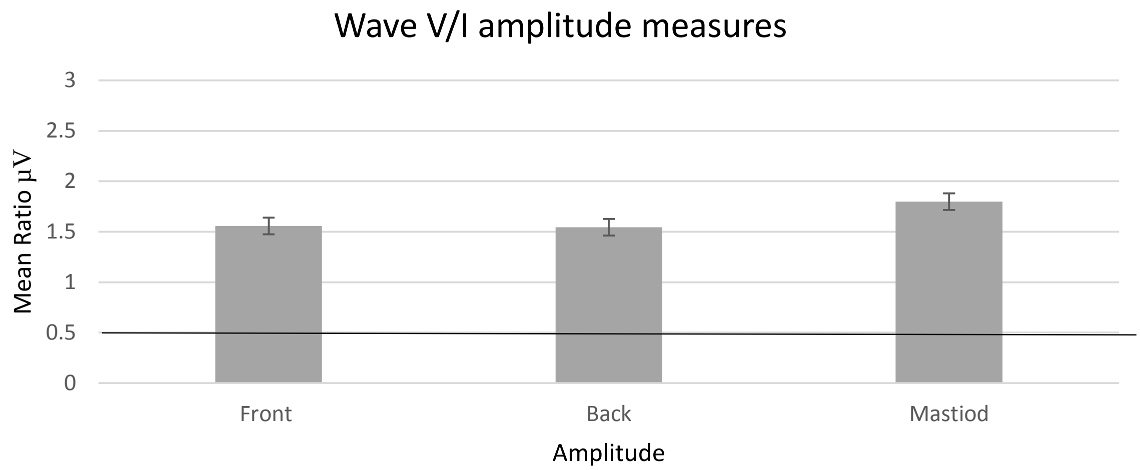


*Figure 12.* Wave V amplitude measures for all electrode montages. Solid black line at 0.5 µV indicates cutoff value for a normal amplitude measurement. Error bars indicate a 95% confidence interval.

Table 14.1

*Tests of within-subjects effects for amplitude ratio on electrode montage and gender.*

| Source | | Type III Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|---|
| Montage | Sphericity Assumed | 1.675 | 2 | .837 | 5.072 | .010 |
| | Greenhouse-Geisser | 1.675 | 1.367 | 1.225 | 5.072 | .021 |
| Gender | Sphericity Assumed | .466 | 1 | .466 | .462 | .503 |
| | Greenhouse-Geisser | .466 | 1.000 | .466 | .462 | .503 |

*Note.* Shaded areas indicate adjusted calculation used.

Table 14.2

*ANOVA pairwise comparisons for amplitude ratio electrode montages.*

| | | | | | 95% Confidence Interval for Difference | |
|---|---|---|---|---|---|---|
| (I) montage | (J) montage | Mean Difference (I-J) | Std. Error | Sig. | Lower Bound | Upper Bound |
| Front | Back | .013 | .045 | 1.000 | -.103 | .129 |
| | Mastoid | -.213 | .090 | .078 | -.444 | .018 |
| Back | Front | -.013 | .045 | 1.000 | -.129 | .103 |
| | Mastoid | -.226 | .094 | .074 | -.468 | .016 |
| Mastoid | Front | .213 | .090 | .078 | -.018 | .444 |
| | Back | .226 | .094 | .074 | -.016 | .468 |

*Note.* Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni.

Table 14.3

*ANOVA pairwise comparisons for gender.*

| | | | | | 95% Confidence Interval for Difference | |
|---|---|---|---|---|---|---|
| (I) gender | (J) gender | Mean Difference (I-J) | Std. Error | Sig. | Lower Bound | Upper Bound |
| Female | Male | .109 | .161 | .503 | -.222 | .441 |
| Male | Female | -.109 | .161 | .503 | -.441 | .222 |

*Note.* Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni.

Table 15

*Mean latencies of wave V for slow and fast click rates three electrode montages*

| Wave V | 19.1 clicks/sec | 61.1 clicks/sec | Rate Shift |
|---|---|---|---|
| Front of the earlobe | 5.68 | 6.06 | 0.38 |
| Back of the earlobe | 5.67 | 6.05 | 0.38 |
| Mastoid | 5.67 | 6.04 | 0.37 |

*Note*. Mean latency for wave V comparing the slow and fast click rate. The difference between the click rates results in the rate shift.

**Effect of Stimulus Rate**

In the present study, ABRs for all participants were recorded to a 90 dBnHL click stimulus presented at a slow rate (19.1 clicks per second) and a fast rate (61.1 clicks per second). A latency shift was seen as expected as a function of rate in a normally functioning system. The differences between the absolute latency values for wave V at the slow and fast rate were analyzed and averaged for each participant, ear, and montage. The mean latencies for wave V for all montages at the slow click rate and fast rate are shown below in Table 15**.** The difference in latencies of wave V between the slow and fast rate were also calculated and are shown in Figure 13. As shown in Figure 13, there were no obvious differences between wave V latencies and electrode montages across click rates. There were differences in latency at the expected intervals, between the fast and slow rates, as is expected when increasing click rates. The largest difference was 0.38 ms for the front and back of the earlobe which was within normal limits. The smallest difference was 0.37 ms for the mastoid electrode placement, again within normal limits for a normal ABR. The variability between montages was small and not significant. The wave V latency difference between the slow rate and fast rate for the mean of all participants shifted outward at the expected interval. The individual data of all participants' result of rate change can be found in Appendix G**.**

A 2x3x2 (stimulus rate, electrode montage, and gender) mixed ANOVA was conducted. Mauchly's test indicated that the assumption of sphericity was not violated. The results indicate that there were no statistically significant differences between electrode montages, $F(2,50) = 1.298$, $p = 0.282$ (Table 16.2). There were significant differences between the slow and fast stimulus rates as is clinically expected with

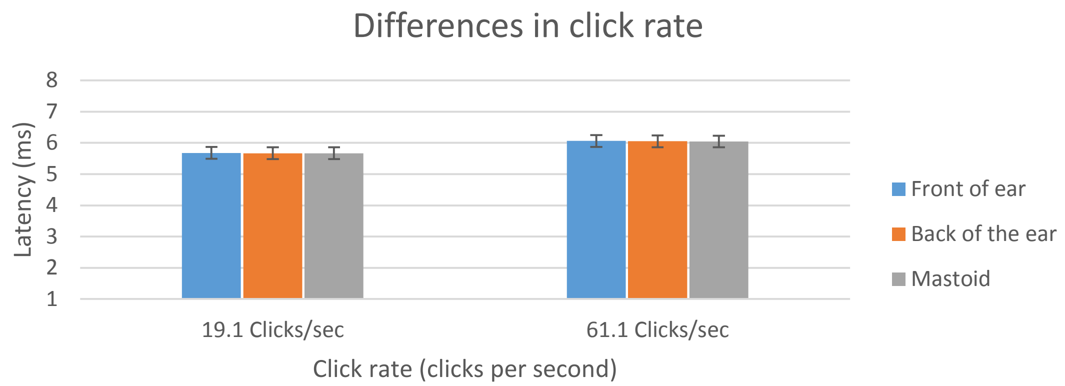


*Figure 13.* Differences between slow and fast click rates for three electrode montages.

Table 16.1

*Tests of within-subjects effects for different stimulus rates, electrode montage and gender.*

| Source | Type III Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Rate | 10.988 | 1 | 10.988 | 1289.814 | .000 |
| Montage | .007 | 2 | .004 | 1.298 | .282 |
| Gender | .927 | 1 | .927 | 13.892 | .001 |

*Note.* Mauchly's test was not significant and spericity was assumed for waveforms, montages, genders, and ears.

Table 16.2

*ANOVA pairwise comparisons for electrode montage.*

| (I) montage | (J) montage | Mean Difference (I-J) | Std. Error | Sig. | 95% Confidence Interval for Difference | |
|---|---|---|---|---|---|---|
| | | | | | Lower Bound | Upper Bound |
| Front | Back | .006 | .007 | 1.000 | -.012 | .025 |
| | Mastoid | .012 | .008 | .424 | -.008 | .032 |
| Back | Front | -.006 | .007 | 1.000 | -.025 | .012 |
| | Mastoid | .006 | .007 | 1.000 | -.013 | .024 |
| Mastoid | Front | -.012 | .008 | .424 | -.032 | .008 |
| | Back | -.006 | .007 | 1.000 | -.024 | .013 |

*Note*. Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni

Table 16.3

*ANOVA pairwise comparisons for fast and slow stimulus rate.*

| (I) rate | (J) rate | Mean Difference (I-J) | Std. Error | Sig. | 95% Confidence Interval for Difference | |
|---|---|---|---|---|---|---|
| | | | | | Lower Bound | Upper Bound |
| Fast | Slow | .375 | .010 | .000 * | .354 | .397 |
| Slow | Fast | -.375 | .010 | .000* | -.397 | -.354 |

*Note.* * = The mean difference is significant at the .05 level. Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni

Table 16.4

*ANOVA pairwise comparisons for gender.*

| | | | | | 95% Confidence Interval for Difference | |
|---|---|---|---|---|---|---|
| (I) gender | (J) gender | Mean Difference (I-J) | Std. Error | Sig. | Lower Bound | Upper Bound |
| Female | Male | -.109 | .029 | .001* | -.169 | -.049 |
| Male | Female | .109 | .029 | .001* | .049 | .169 |

*Note.* * = The mean difference is significant at the .05 level Based on estimated marginal means. Adjustment for multiple comparisons: Bonferroni different stimulus rates on wave V shifts, $F(1,25) = 1289.8$, $p = 0.00$ (Tables 16.1-16.4). There was a significant interaction between stimulus rate and gender, $F(1, 25) = 5.697$, $p = 0.025$. There were no other significant interactions that occurred between variables.

**Effects of Stimulus Polarity on the Response**

For the purpose of this study, rarefaction and condensation click stimulus were recorded for each participant, ear, and electrode montage to investigate any evidence of ANSD. For all participants, there were no signs of inversion of waves which indicated a normally functioning system. Absolute latencies for both rarefaction and condensation clicks occurred at similar latencies and all within the Towson University normative data for the IHS Smart EP system. Data on absolute latency values for all participants at 90 dBnHL for condensation clicks can be examined in Appendix H**.** As there were no indications of ANSD in any participants, no further analyses were conducted using condensation click stimulus.

# Chapter 5

# Discussion

In the present study, click evoked ABRs were recorded at 90 dBnHL for three different electrode montages, and two stimulus rates, for male and female participants, for right and left ears. Absolute latency values were measured for all 30 participants, for a total of 60 ears, for three different electrode montages. All absolute latency values were within normal limits based on the Towson University normative data on the IHS SmartEP System. The Towson University normative data are similar to data collected by Hood (1998), indicating similar latencies across studies. There were no statistically significant differences in absolute latency between electrode montages or ears. Similar to absolute latency, interpeak latencies of waves I-III, III-V, and I-V were within normal limits and there were no statistically significant differences in interpeak latencies between electrode montages. Wave V/I amplitude ratios were within normal limits for all participants and there were no statistically significant differences between electrode montages or genders. Effects of a slow and fast stimulus rate on ABR recordings were calculated and there were no statistically significant differences between electrode montages as a factor of stimulus rate. Although there were no statistically significant differences between ears and montages for all participants, there were statistically significant differences seen between male and female participants.

## Gender Differences

Significant gender differences were found in absolute latency data. Similar findings had been reported from previous ABR studies as well. Females often have larger wave V amplitudes, shorter interpeak latencies, and shorter absolute latencies for waves III and V (Don, Ponton, Eggermont, & Masuda, 1993; Jerger & Hall, 1980; Stockard et al., 1979). Don et al. (1993) investigated some of the possible physiological reasons for differences in ABR response measures due to gender. These researchers found females had 13% shorter cochlear travel times compared to men. Females had faster response times for a stimulus to arrive at wave V generators, and better VIII nerve neural synchrony compared to males. These differences resulted in larger wave V amplitudes for females (Don et al., 1993). Don and colleagues (1993) speculated that the difference in cochlear response time was due to the shorter length and steeper stiffness gradient of the cochlea for females. Stockard et al. (1979) also noted that females had a small difference in pathway length from the acoustic nerve to the midbrain compared to males, which could be responsible for the notable gender differences.

Gender differences may also be related to head size differences. The greater the head size, the greater the expected latency values for wave V and I-V interpeak latency values, which could result in the observed gender differences (Dempsey et al., 1986). Dempsey et al. (1986) found that there was a relationship between brain size (as reflected by head size), and the latency differences observed. Trune and colleagues (1988) observed greater latency values in larger head sizes and reported that as head size increases, there was an increase in absolute latency values. However, when ABRs are recorded for different genders, matched for head size, females still had shorter latencies compared to males (Dempsey, Censoprano, & Mazor, 1986; Stockard et al., 1979; Trune, Mitchell, & Phillips, 1988). This finding indicated that although head size played a factor in latency, if a male and female have the same head size, then females will have shorter latency values.

Male and female core body temperatures have also been investigated as possible causes of gender differences in ABR measurements. Males have a higher average core temperature by about three degrees Celsius compared to females (Hall, 2007). Hall (2007) reported that even though there is a core temperature difference between genders, it was not enough to result in any latency differences. There were no differences based on body temperature in absolute latency values unless there were extreme temperature changes, like in cases of hyperthermia (Hall, 2007).

The statistically significant differences that were seen in this study were similar to the findings of other studies. Recall there was a statistically significant difference between genders when combined for ears. As previously described, anatomical differences between males and females, including head size differences, can cause significant difference between genders in ABR recordings. Therefore, it was not surprising that in the current study statistically significant gender differences were also identified. A limitation to this study was that head size was not measured in this study, therefore there was no way to determine if the longer latencies in males were indeed due to differences in head size or just due to an overall gender difference, regardless of head size. Although there were gender differences, the ABR measurements were all within normal limits for a normal ABR for both males and females. While the findings were statistically significant, they were not clinically significant. Therefore, this study doesn't support the need for separate normative data based on gender.

**Absolute Latency Measurements/ Interpeak Differences**

All latency values were within normal limits based on the Towson University normative data on the IHS SmartEP System. There were no statistically significant differences between montages in terms of absolute latency values. Interpeak latencies of waves I-III, III-V, and I-V were also measured in all participants for all montages and were within normal limits and there were no statistically significant differences between montages.

The finding that all latency measurements were within normal limits was as expected based on prior literature. ABRs are a far field recorded potential where the electrodes are placed far from the potential generator. The earlobes and mastoids are close enough to the potential generator, or cochlea, for resulting latencies to be within normal limits (Pethe, Muhler, & von Specht, 1998; Terkildsen & Osterhammel, 1981). Terkildsen and Osterhammel (1981) noted that ABR responses would be present within normal limits when electrodes were placed close to the potential generator. In the literature, if the electrode is placed on either the earlobe or mastoid, normal latency values are expected in an ideal participant (Beattie, et al., 1986; Berlin & Dobie, 1979). Some researchers prefer placing the inverting electrode on the back of the neck rather than the mastoid of earlobe, but that placement was not examined in this study. Beattie et al. (1986) found that there were no obvious latency differences between electrode montages, regardless of inverting electrode placement. Berlin and Dobie (1979) however, recommended that the inverting electrode be placed on the mastoid for the best latency of wave I. However, in the current study there were no latency differences for wave I using the mastoid electrode placement compared to the earlobes. There were no further studies comparing the mastoid placement to the earlobes specifically.

**Amplitude Differences**

In the current study, there were no significant differences in the V/I amplitude ratio based on the electrode montage used. All amplitude ratios were above the 0.5 µV cutoff indicating normal amplitude measurements. This cutoff criteria was based on the Don and Kwong (2009) statement that any V/I amplitude ratio below the value was indicative of a retrocochlear pathology, and considered abnormal. Amplitude differences with the mastoid electrode placement were greater than the front and back earlobe electrode placement based on descriptive statistics, but the differences were not statistically significant between montages. Prior studies found that when using an earlobe electrode montage compared to other montages, there were greater Wave I amplitudes compared to the other waveforms (Erwin, & Husain, 2015; Katbamna et al., 1996; Pethe et al., 1998; Terkildsen & Osterhammel, 1981). Pethe et al. (1998) found that when using the mastoid electrode montage compared to the earlobe electrode, there were greater amplitude values in wave V. Beattie et al. (1986) determined that there were several more optimal places for electrodes that would result in the best amplitudes of waves, such as the nape of the neck, but those were not utilized in this study.

**Stimulus Rate**

For all electrode montages, stimulus rates were recorded using both slow and fast click stimuli. There were no statistically significant differences in latency between electrode montages between the slow and fast stimulus rates. There was the expected outward shift in wave V latency when changing from a slow to faster stimulus rate. This increase in rate places stress on the auditory system causing less recovery time (Hall, 2007; Pratt et al., 1981). For every increase in 10 clicks per second, there is an expected latency shift of approximately 0.1 ms in wave V latency (Daley et al., 1977). In the current study, there was an increase in stimulus rate of 40 clicks per second; therefore, a shift of 0.4 ms is expected in wave V latency. The current study found latency differences of 0.37-0.38 ms, in agreement with the expected results reported by Daley et al. (1977). There were no differences between electrode montages in the expected shift in latency for wave V, indicating no montage resulted in a greater latency shift with rate changes.

**Morphology**

Overall replicability and morphology of the ABR was observed in each participant and for each electrode montage. Between each participant, there were different morphological forms, but all considered to be normal. One of the most common forms is the wave IV/V complex (Hood, 2015). In the current study 19 participants had a wave IV/V complex. Although there can be some differences in shape, each response and montage had identifiable waves I, III, and V. All responses were obtained using at least two trials for each test condition, or until the waveforms were repeatable.

In the present study, the vast majority of the ABRs recorded were repeatable with two trials, and their overall morphology was judged to be very good. A small number of ABR recordings were repeated more than two times, due to a high rejection rate. Replicable responses are imperative for accurate values once the waves are summed. Eight participants had more than two trials due to a high number of rejections, and problems with repeatability.

**Post auricular muscle response.**

One morphological difference seen between electrode montages was the presence of PAM (Figure 4). PAM responses were seen in six of the mastoid electrode recordings, and was absent in both the front and back earlobe electrode placements for all participants. The presence of PAM in the recordings did not interfere with any of the absolute latency values. The PAM response is a sound evoked compound action potential that is recorded from the post auricular muscle, which is located behind the pinna (Talaat, Kabel, Khalil, & Said, 2010). Since the mastoid electrode placement is closer to the post auricular muscle than the earlobe, a PAM response is more likely with the mastoid placement. Due to the likelihood of recording PAM when using the mastoid placement, several researchers have encouraged professionals to use more electrically silent locations for electrode placement (Beattie et al., 1986; Stephenson & Gibbs, 1951). If a professional is not sure if the positive deflection in a mastoid recording is PAM, stimulus intensity should be decreased. When the stimulus intensity is decreased there should be an overall decrease in PAM. Although PAM was only present for the mastoid electrode placement, it did not affect latency values; therefore this study did not provide support for the exclusion of the mastoid electrode placement.

**Stimulus Polarity**

Rarefaction and condensation clicks were recorded for all participants and electrode montages. The purpose of reversing the stimulus polarity was to identify individuals with ANSD. If a participant were to have ANSD, there would be an inversion of waves I, III, and V when polarity changed (Berlin et al., 2009). An inversion is created when there is a response from the outer hair cells, rather than from the VIII nerve and auditory brainstem (Berlin et al., 2009). There were no inversions of waves observed for all participants and all electrode montages in the current study. This indicated that none of the participants had ANSD. These results were expected, since there were no other otologic symptoms noted in any of the participants to suggest ANSD.

**Important Considerations for Clinical Application**

Results of this study indicate that there were no significant amplitude or latency differences between electrode montages; therefore, there was no support to indicate one electrode placement would be a better clinical option over another. The front of the earlobe, back of the earlobe, and mastoid electrode montage all resulted in similar latency values, amplitudes, and morphology. This is clinically relevant because there are certain conditions where a professional may wish to use one electrode placement over another. If a patient has heavy scaring or large holes in the earlobes, the mastoid placement may yield more accurate recordings. The same can be said of a patient who has a particularly hairy mastoid. To be able to have better contact with the skin, an earlobe electrode placement can be utilized instead. The back of the earlobe may be chosen because it can be more cosmetically appealing. Scrubbing may result in some redness and when placed on the back of the earlobe the redness will not be visible to others. Professionals can also choose different electrode placements if they are unable to reach a location due to cultural clothing limitations, or an absent pinna due to trauma or birth defect.

Professionals should use the electrode placement that they are most comfortable with when applying an electrode to yield the lowest impedance value. Having the best skin connection will result in less rejections and better replicability in the waveforms. It is important to note that although gender differences were found in this study, there were no differences that resulted in latencies that were outside of pre-existing normative data. Therefore, while it is important that professionals know that there are potential differences between genders and latencies when marking waveforms, gender based normative data is not warranted. If audiologists were to establish normative data for their own equipment it would be imperative to ensure there are an equal number of males and females when collecting data.

**Future Studies**

The current study did not measure head size of the participants. A future study should follow a similar methodology, with the addition of measuring head size for all participants. It would be interesting to identify if there were still similar gender differences as in the current study, and if head size played a role in absolute latency values. Another study using more participants and the same electrode montages should also be completed to determine if the same significant gender difference would be observed with a larger participant pool.

# Appendix A

IRB Protocol Approval # 1608003488 Inbox x

Taylor, Amy L. <altaylor@towson.edu> 10/4/16
to me, Diana, IRB

Dear Ms. Gartner,
The IRB has approved your protocol "The Effect of the Electrode Placement on the Auditory Brainstem Response (ABR) on Amplitude, Morphology, and Latency " effective 10/4/2016 as Expedited review, Category 4.

Your IRB protocol can now be viewed by your faculty advisor in MyOSPR. For more information, please visit: http://www.towson.edu/academics/research/sponsored/myospr.html

If you should encounter any new risks, reactions, or injuries to subjects while conducting your research, please notify IRB@towson.edu. Should your research extend beyond one year in duration, or should there be substantive changes in your research protocol, you will need to submit another application.

We are offering training and orientation sessions for faculty in the fall, I encourage your advisor to sign up for one of the sessions: http://fusion.towson.edu/www/signupGeneric/index.cfm?type=OSPR

Regards,
Towson IRB

Amy L. Taylor, MBA, CRA · Assistant Vice President for Research
Office of Sponsored Programs & Research
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TOWSON UNIVERSITY

## Appendix B

### INFORMED CONSENT FORM

**Project Title: The Effect of the Electrode Placement on the Auditory Brainstem Response (ABR) Amplitude, Morphology, and Latency**

**Principal Investigator:**
Alexandra Gartner, B.A.
(518) 496-2388
agartn3@students.towson.edu

The purpose of this thesis project is to collect data on the Auditory Brainstem Response (ABR) and the effect of the electrode placement on the amplitude (height), latency (timing) and morphology (shape). The goal is to determine whether one electrode position (front of the ear, back of the ear, and mastoid) results in earlier latencies, greater amplitude and better morphology. While the electrode positions being chosen for this study have been tested in the past they have never been compared in one comprehensive study using the same participants. Your role in this project will consist of attending one two-hour session. Eventually the data collected will be used to improve the clinical electrode protocol used at Towson University.

At the test session, you will be asked some questions about your hearing history, have your hearing screened, and have an ABR recorded. The session itself consists of the test administrator placing eight electrodes over the surface of the head and earlobes and have to foam plugs placed in your ear canals. You will then be instructed to get comfortable and relax in a reclining chair while listening to clicks in your ears. There are no known risks or discomforts associated with this procedure.

Participation in this study is voluntary. All information will remain strictly confidential. Although the descriptions and findings may be published, at no time will your name be used. All data obtained electronically will be password protected and any personal identification will be removed. All paper information collected during the study will be kept strictly confidential and will be located in a locked cabinet in a locked office or laboratory. You are at liberty to withdraw your consent to the experiment and discontinue participation at any time without prejudice. If you have any questions after today, please feel free to call (410)704-2417 and ask for Dr. Emanuel, or contact Dr. Deborah Gartland, Chairperson of the Institutional Review Board for the Protection of Human Participants at Towson University at (410) 704-2236.

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I, ________________________________, affirm that I have read and understood the above statement and have had all of my questions answered.
Signature: ________________________________ Date: __________________
Witness: _________________________________ Date: ___________________
THIS PROJECT HAS BEEN REVIEWED BY THE INSTITUTIONAL REVIEW BOARD FOR THE PROTECTION OF HUMAN PARTICIPANTS AT TOWSON UNIVERSITY.

# Appendix C

Date__________ Participant number ________________

Case History Questions

Gender_________________

Do you have any tinnitus (ringing in ears)? Yes No

Right ear Left ear Both

Family History of hearing loss? Yes No Who_________________

Aural Fullness? Yes No

History of hearing loss? Yes No

When last tested and where ___________________________________

Results _________________________________

History of noise exposure? Yes No Explain____________________

Chronic ear infections? Yes No

Any ear pain? Yes No

Any dizziness? Yes No

History of ear surgeries? Yes No

Results of otoscopy: Right ear:

Left ear:

**Pure Tone testing results**

| | **250 Hz** | **500 Hz** | **1000 Hz** | **2000 Hz** | **4000 Hz** | **8000 Hz** |
|---|---|---|---|---|---|---|
| **Right ear** | | | | | | |
| **Left ear** | | | | | | |

**Tympanometry:**

**Right _________ Left___________**

Contralateral reflexes

| | 500 Hz | 1000 Hz | 2000 Hz |
|---|---|---|---|
| Right Ear | | | |
| Left Ear | | | |

**Impedance Check**

Beginning ________Middle ________End _________

**Appendix D**

*Mean latencies for all participants and three electrode montages for a 90 dB nHL rarefaction click.*

| Participant Number | Wave I Front | Wave I Back | Wave I Mastoid | Wave III Front | Wave III Back | Wave III Mastoid | Wave V Front | Wave V Back | Wave V Mastoid |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.58 | 1.6 | 1.63 | 3.7 | 3.7 | 3.65 | 5.65 | 5.65 | 5.65 |
| 2 | 1.68 | 1.68 | 1.58 | 3.83 | 3.8 | 3.78 | 5.83 | 5.8 | 5.8 |
| 3 | 1.48 | 1.55 | 1.48 | 3.68 | 3.73 | 3.7 | 5.6 | 5.5 | 5.5 |
| 4 | 1.5 | 1.53 | 1.48 | 3.65 | 3.6 | 3.58 | 5.53 | 5.58 | 5.55 |
| 5 | 1.78 | 1.85 | 1.78 | 3.85 | 3.9 | 3.78 | 5.47 | 5.45 | 5.55 |
| 6 | 1.73 | 1.65 | 1.65 | 3.73 | 3.78 | 3.75 | 5.55 | 5.53 | 5.58 |
| 7 | 1.45 | 1.4 | 1.43 | 3.5 | 3.58 | 3.48 | 5.58 | 5.58 | 5.58 |
| 8 | 1.5 | 1.45 | 1.45 | 3.58 | 3.58 | 3.58 | 5.45 | 5.53 | 5.53 |
| 9 | 1.5 | 1.55 | 1.43 | 3.88 | 3.85 | 3.88 | 5.58 | 5.58 | 5.65 |
| 10 | 1.38 | 1.43 | 1.5 | 3.85 | 3.9 | 3.83 | 5.65 | 5.68 | 5.78 |
| 11 | 1.55 | 1.58 | 1.6 | 3.8 | 3.85 | 3.78 | 5.8 | 5.85 | 5.83 |
| 12 | 1.45 | 1.43 | 1.45 | 3.83 | 3.83 | 3.75 | 5.85 | 5.9 | 5.9 |
| 13 | 1.48 | 1.5 | 1.5 | 3.88 | 3.9 | 3.83 | 5.6 | 5.58 | 5.58 |
| 14 | 1.58 | 1.6 | 1.55 | 3.85 | 3.85 | 3.73 | 5.7 | 5.63 | 5.72 |
| 15 | 1.75 | 1.65 | 1.65 | 3.7 | 3.68 | 3.7 | 5.65 | 5.7 | 5.68 |
| 16 | 1.68 | 1.65 | 1.68 | 3.93 | 3.9 | 3.83 | 5.55 | 5.6 | 5.55 |
| 17 | 1.45 | 1.33 | 1.25 | 3.85 | 3.85 | 3.75 | 5.68 | 5.65 | 5.72 |
| 18 | 1.23 | 1.5 | 1.35 | 3.9 | 3.85 | 3.93 | 5.78 | 5.88 | 5.68 |
| 19 | 1.55 | 1.6 | 1.6 | 3.85 | 3.88 | 3.75 | 5.6 | 5.63 | 5.6 |
| 20 | 1.63 | 1.68 | 1.58 | 3.78 | 3.8 | 3.7 | 5.72 | 5.65 | 5.6 |
| 21 | 1.48 | 1.4 | 1.5 | 3.85 | 3.9 | 3.98 | 5.78 | 5.72 | 5.78 |
| 22 | 1.43 | 1.43 | 1.38 | 3.93 | 3.85 | 3.83 | 5.78 | 5.7 | 5.78 |
| 23 | 1.63 | 1.6 | 1.43 | 3.7 | 3.73 | 3.85 | 5.5 | 5.53 | 5.47 |
| 24 | 1.65 | 1.78 | 1.53 | 3.83 | 3.83 | 3.88 | 5.7 | 5.65 | 5.75 |
| 25 | 1.53 | 1.53 | 1.5 | 4.1 | 4.15 | 4.1 | 5.85 | 5.9 | 5.88 |
| 26 | 1.5 | 1.55 | 1.63 | 3.98 | 3.95 | 3.95 | 5.78 | 5.8 | 5.78 |
| 27 | 1.65 | 1.65 | 1.68 | 3.7 | 3.68 | 3.68 | 5.78 | 5.68 | 5.68 |
| 28 | 1.7 | 1.65 | 1.68 | 3.73 | 3.75 | 3.73 | 5.65 | 5.55 | 5.6 |
| 29 | 1.88 | 1.88 | 1.9 | 3.83 | 3.88 | 3.83 | 5.9 | 5.9 | 5.85 |
| 30 | 1.68 | 1.88 | 1.9 | 3.85 | 3.83 | 3.9 | 5.85 | 5.9 | 5.93 |
| 31 | 1.65 | 1.65 | 1.55 | 3.88 | 3.93 | 3.9 | 5.88 | 5.85 | 5.7 |
| 32 | 1.5 | 1.5 | 1.5 | 3.95 | 3.98 | 3.98 | 5.85 | 5.9 | 5.9 |
| 33 | 1.73 | 1.75 | 1.78 | 4 | 4 | 3.98 | 5.72 | 5.85 | 5.65 |
| 34 | 1.68 | 1.75 | 1.83 | 3.93 | 3.95 | 3.88 | 5.47 | 5.53 | 5.78 |
| 35 | 1.58 | 1.63 | 1.6 | 3.75 | 3.78 | 3.8 | 5.65 | 5.65 | 5.65 |
| 36 | 1.68 | 1.63 | 1.58 | 3.85 | 3.85 | 3.8 | 5.78 | 5.72 | 5.78 |

Appendix D continued

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 37 | 1.55 | 1.53 | 1.55 | 3.85 | 3.85 | 3.83 | 5.53 | 5.58 | 5.53 |
| 38 | 1.58 | 1.5 | 1.5 | 3.88 | 3.9 | 3.78 | 5.53 | 5.47 | 5.47 |
| 39 | 1.8 | 1.7 | 1.7 | 4.08 | 4.08 | 4.15 | 5.83 | 5.8 | 5.75 |
| 40 | 1.8 | 1.75 | 1.75 | 4.05 | 4.08 | 4.2 | 5.9 | 5.88 | 5.8 |
| 41 | 1.38 | 1.5 | 1.4 | 3.75 | 3.85 | 3.78 | 5.53 | 5.53 | 5.5 |
| 42 | 1.48 | 1.4 | 1.5 | 3.68 | 3.75 | 3.7 | 5.53 | 5.53 | 5.53 |
| 43 | 1.7 | 1.73 | 1.55 | 3.9 | 3.98 | 3.95 | 5.75 | 5.78 | 5.8 |
| 44 | 1.78 | 1.83 | 1.78 | 3.78 | 3.78 | 3.85 | 5.72 | 5.65 | 5.63 |
| 45 | 1.75 | 1.73 | 1.7 | 3.75 | 3.83 | 3.8 | 5.7 | 5.65 | 5.75 |
| 46 | 1.78 | 1.73 | 1.75 | 3.78 | 3.78 | 3.8 | 5.78 | 5.58 | 5.43 |
| 47 | 1.5 | 1.5 | 1.5 | 4.1 | 4.18 | 4.1 | 5.72 | 5.78 | 5.78 |
| 48 | 1.65 | 1.63 | 1.6 | 4.1 | 4.08 | 4.1 | 5.72 | 5.72 | 5.78 |
| 49 | 1.5 | 1.48 | 1.65 | 3.65 | 3.7 | 3.55 | 5.35 | 5.3 | 5.3 |
| 50 | 1.63 | 1.75 | 1.73 | 3.58 | 3.6 | 3.58 | 5.5 | 5.43 | 5.33 |
| 51 | 1.58 | 1.58 | 1.6 | 3.63 | 3.6 | 3.6 | 5.38 | 5.35 | 5.4 |
| 52 | 1.53 | 1.53 | 1.68 | 3.83 | 3.88 | 3.85 | 5.5 | 5.5 | 5.43 |
| 53 | 1.43 | 1.45 | 1.5 | 3.55 | 3.58 | 3.55 | 5.53 | 5.58 | 5.55 |
| 54 | 1.35 | 1.38 | 1.38 | 3.7 | 3.8 | 3.65 | 5.63 | 5.58 | 5.63 |
| 55 | 1.68 | 1.68 | 1.85 | 3.98 | 3.95 | 3.98 | 5.9 | 5.85 | 5.88 |
| 56 | 1.58 | 1.58 | 1.46 | 4.03 | 3.95 | 3.88 | 5.85 | 5.83 | 5.78 |
| 57 | 1.65 | 1.55 | 1.68 | 3.94 | 3.95 | 3.93 | 5.78 | 5.78 | 5.78 |
| 58 | 1.45 | 1.5 | 1.65 | 3.95 | 3.85 | 3.98 | 5.8 | 5.83 | 5.8 |
| 59 | 1.53 | 1.63 | 1.63 | 3.98 | 4.08 | 3.93 | 5.78 | 5.68 | 5.65 |
| 60 | 1.6 | 1.65 | 1.73 | 3.98 | 3.95 | 3.95 | 5.72 | 5.78 | 5.78 |

*Note.* All values measured in ms

**Appendix E**

Table 3. *Interpeak latency values for all participants and three electrode montages for a 90 dBnHL rarefaction click*

| Participant Number | III-I Front | III-I Back | III-I Mastoid | V-III Front | V-III Back | V-III Mastoid | V-I Front | V-I Back | V-I Mastoid |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.13 | 2.1 | 2.03 | 1.95 | 1.95 | 2 | 4.08 | 4.05 | 4.03 |
| 2 | 2.15 | 2.13 | 2.2 | 2 | 2 | 2.03 | 4.15 | 4.13 | 4.22 |
| 3 | 2.2 | 2.17 | 2.23 | 1.92 | 1.78 | 1.8 | 4.13 | 3.95 | 4.03 |
| 4 | 2.15 | 2.08 | 2.1 | 1.88 | 1.98 | 1.97 | 4.03 | 4.05 | 4.07 |
| 5 | 2.08 | 2.05 | 2 | 1.62 | 1.55 | 1.78 | 3.7 | 3.6 | 3.78 |
| 6 | 2.05 | 2.13 | 2.1 | 1.82 | 1.75 | 1.83 | 3.83 | 3.88 | 3.93 |
| 7 | 2.08 | 2.18 | 2.03 | 2.05 | 2.03 | 2.03 | 4.13 | 4.2 | 4.13 |
| 8 | 2.08 | 2.13 | 2.13 | 1.88 | 1.95 | 1.95 | 3.95 | 4.08 | 4.08 |
| 9 | 2.28 | 2.3 | 2.45 | 1.7 | 1.73 | 1.78 | 4.08 | 4.03 | 4.23 |
| 10 | 2.48 | 2.47 | 2.33 | 1.8 | 1.78 | 1.95 | 4.28 | 4.25 | 4.28 |
| 11 | 2.25 | 2.28 | 2.17 | 2 | 2 | 2.05 | 4.25 | 4.27 | 4.22 |
| 12 | 2.38 | 2.4 | 2.3 | 2.02 | 2.08 | 2.15 | 4.4 | 4.48 | 4.45 |
| 13 | 2.4 | 2.4 | 2.33 | 1.72 | 1.68 | 1.75 | 4.13 | 4.08 | 4.08 |
| 14 | 2.28 | 2.25 | 2.17 | 1.85 | 1.78 | 2 | 4.13 | 4.03 | 4.18 |
| 15 | 1.95 | 2.03 | 2.05 | 1.95 | 2.03 | 1.97 | 3.9 | 4.05 | 4.03 |
| 16 | 2.25 | 2.25 | 2.15 | 1.63 | 1.7 | 1.72 | 3.88 | 3.95 | 3.88 |
| 17 | 2.4 | 2.53 | 2.5 | 1.82 | 1.8 | 1.97 | 4.22 | 4.33 | 4.47 |
| 18 | 2.67 | 2.35 | 2.57 | 1.88 | 2.03 | 1.75 | 4.55 | 4.38 | 4.32 |
| 19 | 2.3 | 2.28 | 2.15 | 1.75 | 1.75 | 1.75 | 4.05 | 4.03 | 4 |
| 20 | 2.15 | 2.13 | 2.13 | 1.95 | 1.85 | 1.9 | 4.1 | 3.98 | 4.02 |
| 21 | 2.38 | 2.5 | 2.48 | 1.93 | 1.82 | 1.8 | 4.3 | 4.32 | 4.28 |
| 22 | 2.5 | 2.42 | 2.55 | 1.85 | 1.85 | 1.85 | 4.35 | 4.28 | 4.4 |
| 23 | 2.08 | 2.13 | 2.43 | 1.8 | 1.8 | 1.62 | 3.88 | 3.93 | 4.05 |
| 24 | 2.18 | 2.05 | 2.35 | 1.88 | 1.83 | 1.88 | 4.05 | 3.88 | 4.22 |
| 25 | 2.57 | 2.63 | 2.6 | 1.75 | 1.75 | 1.78 | 4.32 | 4.38 | 4.38 |
| 26 | 2.48 | 2.4 | 2.33 | 1.8 | 1.85 | 1.83 | 4.28 | 4.25 | 4.15 |
| 27 | 2.05 | 2.03 | 2 | 2.08 | 1.92 | 1.92 | 4.13 | 3.95 | 3.93 |
| 28 | 2.03 | 2.1 | 2.05 | 1.93 | 1.8 | 1.87 | 3.95 | 3.9 | 3.93 |
| 29 | 1.95 | 2 | 1.93 | 2.08 | 2.03 | 2.02 | 4.03 | 4.03 | 3.95 |
| 30 | 2.17 | 1.95 | 2 | 2 | 2.08 | 2.03 | 4.18 | 4.03 | 4.03 |
| 31 | 2.23 | 2.28 | 2.35 | 2 | 1.92 | 1.8 | 4.22 | 4.2 | 4.15 |
| 32 | 2.45 | 2.48 | 2.48 | 1.9 | 1.93 | 1.93 | 4.35 | 4.4 | 4.4 |
| 33 | 2.28 | 2.25 | 2.2 | 1.72 | 1.85 | 1.68 | 4 | 4.1 | 3.88 |
| 34 | 2.25 | 2.2 | 2.15 | 1.55 | 1.58 | 1.9 | 3.8 | 3.78 | 3.83 |
| 35 | 2.17 | 2.15 | 2.2 | 1.9 | 1.88 | 1.85 | 4.08 | 4.03 | 4.05 |
| 36 | 2.17 | 2.23 | 2.22 | 1.93 | 1.87 | 1.98 | 4.1 | 4.1 | 4.2 |
| 37 | 2.3 | 2.33 | 2.28 | 1.68 | 1.73 | 1.7 | 3.98 | 4.05 | 3.98 |

Appendix E continued

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 38 | 2.3 | 2.4 | 2.28 | 1.65 | 1.57 | 1.7 | 3.95 | 3.97 | 3.97 |
| 39 | 2.28 | 2.38 | 2.45 | 1.75 | 1.72 | 1.6 | 4.03 | 4.1 | 4.05 |
| 40 | 2.25 | 2.33 | 2.45 | 1.85 | 1.8 | 1.6 | 4.1 | 4.13 | 4.05 |
| 41 | 2.38 | 2.35 | 2.38 | 1.78 | 1.68 | 1.73 | 4.15 | 4.03 | 4.1 |
| 42 | 2.2 | 2.35 | 2.2 | 1.85 | 1.78 | 1.83 | 4.05 | 4.13 | 4.03 |
| 43 | 2.2 | 2.25 | 2.4 | 1.85 | 1.8 | 1.85 | 4.05 | 4.05 | 4.25 |
| 44 | 2 | 1.95 | 2.08 | 1.95 | 1.88 | 1.78 | 3.95 | 3.83 | 3.85 |
| 45 | 2 | 2.1 | 2.1 | 1.95 | 1.83 | 1.95 | 3.95 | 3.93 | 4.05 |
| 46 | 2 | 2.05 | 2.05 | 2 | 1.8 | 1.63 | 4 | 3.85 | 3.68 |
| 47 | 2.6 | 2.67 | 2.6 | 1.63 | 1.6 | 1.68 | 4.22 | 4.28 | 4.28 |
| 48 | 2.45 | 2.45 | 2.5 | 1.63 | 1.65 | 1.68 | 4.07 | 4.1 | 4.18 |
| 49 | 2.1 | 2.23 | 1.9 | 1.7 | 1.6 | 1.75 | 3.8 | 3.83 | 3.65 |
| 50 | 1.95 | 1.85 | 1.85 | 1.92 | 1.82 | 1.75 | 3.88 | 3.68 | 3.6 |
| 51 | 2.05 | 2.03 | 2 | 1.75 | 1.75 | 1.8 | 3.8 | 3.77 | 3.8 |
| 52 | 2.3 | 2.35 | 2.17 | 1.67 | 1.63 | 1.57 | 3.98 | 3.98 | 3.75 |
| 53 | 2.13 | 2.13 | 2.05 | 1.96 | 2 | 2 | 4.1 | 4.13 | 4.05 |
| 54 | 2.35 | 2.42 | 2.28 | 1.92 | 1.78 | 1.98 | 4.28 | 4.2 | 4.25 |
| 55 | 2.3 | 2.28 | 2.13 | 1.93 | 1.9 | 1.9 | 4.23 | 4.18 | 4.03 |
| 56 | 2.45 | 2.38 | 2.4 | 1.82 | 1.88 | 1.9 | 4.27 | 4.25 | 4.3 |
| 57 | 2.3 | 2.4 | 2.25 | 1.84 | 1.83 | 1.85 | 4.13 | 4.23 | 4.1 |
| 58 | 2.55 | 2.35 | 2.33 | 1.85 | 1.98 | 1.82 | 4.4 | 4.33 | 4.15 |
| 59 | 2.45 | 2.45 | 2.3 | 1.8 | 1.6 | 1.73 | 4.25 | 4.05 | 4.03 |
| 60 | 2.38 | 2.3 | 2.23 | 1.75 | 1.83 | 1.83 | 4.13 | 4.13 | 4.05 |

*Note.* Values measured in ms

**Appendix F**

Table 5. *V/I amplitude ratio (µV) for all participants and each montage*

| Participant | V/I amp ratio Front | V/I amp ratio Back | V/I amp ratio Mastoid |
|---|---|---|---|
| 1 | 2.31 | 2.40 | 1.16 |
| 2 | 2.79 | 2.14 | 2.39 |
| 3 | 1.54 | 1.79 | 1.89 |
| 4 | 1.07 | 1.05 | 1.52 |
| 5 | 1.63 | 1.93 | 1.99 |
| 6 | 1.43 | 1.23 | 1.47 |
| 7 | 2.81 | 1.91 | 2.48 |
| 8 | 1.90 | 1.90 | 2.30 |
| 9 | 1.65 | 1.69 | 2.34 |
| 10 | 0.87 | 1.01 | 2.08 |
| 11 | 1.30 | 1.29 | 2.74 |
| 12 | 1.05 | 0.92 | 1.17 |
| 13 | 1.02 | 1.17 | 1.30 |
| 14 | 1.02 | 0.90 | 1.09 |
| 15 | 2.83 | 3.36 | 1.72 |
| 16 | 2.52 | 3.06 | 1.36 |
| 17 | 2.87 | 2.34 | 2.48 |
| 18 | 3.08 | 3.3 | 3.39 |
| 19 | 1.13 | 1.00 | 1.78 |
| 20 | 1.04 | 1.39 | 1.16 |
| 21 | 2.16 | 1.27 | 1.72 |
| 22 | 1.07 | 1.04 | 1.37 |
| 23 | 0.83 | 0.77 | 1.33 |
| 24 | 0.87 | 0.84 | 1.01 |
| 25 | 1.09 | 1.05 | 1.35 |
| 26 | 1.29 | 1.03 | 2.28 |
| 27 | 1.02 | 1.35 | 1.62 |
| 28 | 1.69 | 1.70 | 2.02 |
| 29 | 1.51 | 1.65 | 1.99 |
| 30 | 1.72 | 1.58 | 2.54 |
| 31 | 0.80 | 0.83 | 1.67 |
| 32 | 0.68 | 0.74 | 0.84 |
| 33 | 1.55 | 1.12 | 1.64 |
| 34 | 1.52 | 1.44 | 1.61 |
| 35 | 1.84 | 1.55 | 2.35 |
| 36 | 3.13 | 2.47 | 3.00 |
| 37 | 1.31 | 1.12 | 1.41 |
| 38 | 1.02 | 1.12 | 1.17 |

Appendix F continued

| | | | |
|---|---|---|---|
| 39 | 1.17 | 0.91 | 0.93 |
| 40 | 0.93 | 0.95 | 1.34 |
| 41 | 0.75 | 0.98 | 1.54 |
| 42 | 1.01 | 1.13 | 2.06 |
| 43 | 2.65 | 2.98 | 2.51 |
| 44 | 3.08 | 2.66 | 3.05 |
| 45 | 0.34 | 0.46 | 0.47 |
| 46 | 1.75 | 0.55 | 0.51 |
| 47 | 0.45 | 0.70 | 1.09 |
| 48 | 0.64 | 0.64 | 0.96 |
| 49 | 2.01 | 2.02 | 1.97 |
| 50 | 2.63 | 2.39 | 2.23 |
| 51 | 1.83 | 2.09 | 2.22 |
| 52 | 1.50 | 1.71 | 2.64 |
| 53 | 2.41 | 2.42 | 3.45 |
| 54 | 1.85 | 1.87 | 2.75 |
| 55 | 0.79 | 0.80 | 1.40 |
| 56 | 0.78 | 0.78 | 1.59 |
| 57 | 1.65 | 2.33 | 3.29 |
| 58 | 2.31 | 2.03 | 1.57 |
| 59 | 1.03 | 1.00 | 1.06 |
| 60 | 0.87 | 0.79 | 1.55 |

*Note.* All values measured in μV

**Appendix G**

Table 4. *Slow and fast rate differences between absolute wave V latencies for three recording electrode montages*

| Ear | Front | | Back | | Mastoid | |
|---|---|---|---|---|---|---|
| | 19.1/sec | 61.1/sec | 19.1/sec | 61.1/sec | 19.1/sec | 61.1/sec |
| 1 | 5.65 | 5.90 | 5.65 | 5.90 | 5.65 | 5.83 |
| 2 | 5.60 | 5.78 | 5.50 | 5.80 | 5.50 | 5.80 |
| 3 | 5.58 | 5.78 | 5.58 | 5.75 | 5.58 | 5.78 |
| 4 | 5.80 | 6.23 | 5.85 | 6.25 | 5.83 | 6.23 |
| 5 | 5.70 | 6.00 | 5.63 | 5.93 | 5.72 | 5.95 |
| 6 | 5.60 | 6.00 | 5.63 | 6.03 | 5.60 | 6.13 |
| 7 | 5.78 | 6.20 | 5.80 | 6.13 | 5.78 | 6.15 |
| 8 | 5.65 | 6.08 | 5.55 | 6.10 | 5.60 | 6.00 |
| 9 | 5.72 | 6.18 | 5.85 | 6.18 | 5.65 | 6.13 |
| 10 | 5.53 | 5.90 | 5.58 | 5.93 | 5.53 | 5.90 |
| 11 | 5.53 | 5.93 | 5.53 | 5.93 | 5.53 | 5.85 |
| 12 | 5.72 | 6.03 | 5.65 | 6.03 | 5.63 | 6.03 |
| 13 | 5.78 | 6.03 | 5.58 | 5.90 | 5.43 | 5.85 |
| 14 | 5.50 | 5.65 | 5.43 | 5.65 | 5.33 | 5.65 |
| 15 | 5.38 | 5.55 | 5.35 | 5.75 | 5.40 | 5.63 |
| 16 | 5.53 | 5.90 | 5.58 | 5.90 | 5.55 | 5.78 |
| 17 | 5.90 | 6.18 | 5.85 | 6.15 | 5.88 | 6.20 |
| 18 | 5.47 | 5.95 | 5.45 | 5.93 | 5.55 | 5.93 |
| 19 | 5.58 | 6.10 | 5.58 | 6.05 | 5.65 | 6.13 |
| 20 | 5.65 | 6.03 | 5.70 | 6.05 | 5.68 | 6.03 |
| 21 | 5.68 | 6.08 | 5.65 | 6.08 | 5.72 | 6.10 |
| 22 | 5.78 | 6.28 | 5.72 | 6.28 | 5.78 | 6.25 |
| 23 | 5.50 | 6.10 | 5.53 | 5.93 | 5.47 | 5.93 |
| 24 | 5.90 | 6.20 | 5.90 | 6.10 | 5.85 | 6.18 |
| 25 | 5.88 | 6.15 | 5.85 | 6.08 | 5.70 | 6.18 |
| 26 | 5.65 | 6.05 | 5.65 | 6.05 | 5.65 | 6.08 |
| 27 | 5.90 | 6.20 | 5.88 | 6.40 | 5.80 | 6.28 |
| 28 | 5.72 | 6.18 | 5.72 | 6.30 | 5.78 | 6.20 |
| 29 | 5.78 | 6.16 | 5.78 | 6.18 | 5.78 | 6.10 |
| 30 | 5.72 | 6.18 | 5.78 | 6.18 | 5.78 | 6.23 |
| 31 | 5.83 | 6.05 | 5.80 | 6.00 | 5.80 | 5.98 |
| 32 | 5.53 | 5.80 | 5.58 | 5.80 | 5.55 | 5.78 |
| 33 | 5.45 | 6.00 | 5.53 | 5.88 | 5.53 | 5.95 |
| 34 | 5.85 | 6.40 | 5.90 | 6.28 | 5.90 | 6.28 |
| 35 | 5.60 | 6.10 | 5.58 | 5.93 | 5.58 | 5.95 |
| 36 | 5.72 | 6.05 | 5.65 | 6.05 | 5.60 | 6.00 |
| 37 | 5.85 | 6.23 | 5.90 | 6.30 | 5.88 | 6.23 |
| 38 | 5.78 | 6.05 | 5.68 | 6.05 | 5.68 | 6.10 |
| 39 | 5.47 | 6.20 | 5.53 | 6.20 | 5.78 | 6.18 |
| 40 | 5.53 | 5.98 | 5.47 | 6.00 | 5.47 | 6.03 |

Appendix G continued

| | | | | | | |
|---|---|---|---|---|---|---|
| 41 | 5.53 | 6.08 | 5.53 | 5.88 | 5.50 | 5.93 |
| 42 | 5.75 | 6.18 | 5.78 | 6.20 | 5.80 | 6.23 |
| 43 | 5.70 | 6.13 | 5.65 | 6.00 | 5.75 | 6.03 |
| 44 | 5.35 | 5.78 | 5.3 | 5.78 | 5.30 | 5.68 |
| 45 | 5.50 | 5.65 | 5.50 | 5.70 | 5.43 | 5.58 |
| 46 | 5.63 | 5.90 | 5.58 | 5.90 | 5.63 | 5.90 |
| 47 | 5.85 | 6.18 | 5.83 | 6.18 | 5.78 | 6.10 |
| 48 | 5.55 | 6.05 | 5.53 | 5.98 | 5.58 | 5.95 |
| 49 | 5.65 | 6.13 | 5.68 | 6.08 | 5.78 | 6.08 |
| 50 | 5.55 | 5.85 | 5.6 | 5.98 | 5.55 | 6.03 |
| 51 | 5.78 | 6.13 | 5.88 | 6.18 | 5.68 | 6.10 |
| 52 | 5.78 | 6.15 | 5.70 | 6.15 | 5.78 | 6.23 |
| 53 | 5.70 | 5.95 | 5.65 | 6.03 | 5.75 | 6.10 |
| 54 | 5.85 | 6.25 | 5.90 | 6.25 | 5.93 | 6.30 |
| 55 | 5.85 | 6.23 | 5.90 | 6.18 | 5.90 | 6.20 |
| 56 | 5.78 | 6.15 | 5.72 | 6.13 | 5.78 | 6.18 |
| 57 | 5.83 | 6.18 | 5.80 | 6.18 | 5.75 | 6.08 |
| 58 | 5.72 | 6.30 | 5.78 | 6.30 | 5.78 | 6.20 |
| 59 | 5.80 | 6.20 | 5.83 | 6.18 | 5.80 | 6.18 |
| 60 | 5.78 | 6.08 | 5.68 | 6.10 | 5.65 | 6.15 |

*Note.* All measurements in ms

**Appendix H**

Table X. *Absolute latency values of all participants for three electrode montages for a 90 dBnHL condensation click*

| Ear | Wave I Front | Wave I Back | Wave I Mastoid | Wave III Front | Wave III Back | Wave III Mastoid | Wave V Front | Wave V Back | Wave V Mastoid |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.50 | 1.50 | 1.43 | 3.60 | 3.68 | 3.55 | 5.68 | 5.80 | 5.65 |
| 2 | 1.58 | 1.50 | 1.50 | 3.85 | 3.80 | 3.75 | 5.65 | 5.72 | 5.65 |
| 3 | 1.43 | 1.48 | 1.43 | 3.53 | 3.58 | 3.58 | 5.53 | 5.63 | 5.53 |
| 4 | 1.35 | 1.35 | 1.38 | 3.58 | 3.58 | 3.55 | 5.53 | 5.47 | 5.50 |
| 5 | 1.53 | 1.65 | 1.65 | 3.85 | 3.90 | 3.98 | 5.70 | 5.75 | 5.68 |
| 6 | 1.78 | 1.83 | 1.70 | 3.65 | 3.83 | 3.70 | 5.63 | 5.55 | 5.60 |
| 7 | 1.43 | 1.45 | 1.38 | 3.45 | 3.45 | 3.45 | 5.40 | 5.43 | 5.43 |
| 8 | 1.55 | 1.55 | 1.58 | 3.55 | 3.63 | 3.53 | 5.58 | 5.43 | 5.43 |
| 9 | 1.65 | 1.65 | 1.58 | 3.85 | 3.78 | 3.80 | 5.65 | 5.60 | 5.60 |
| 10 | 1.60 | 1.58 | 1.63 | 3.93 | 3.85 | 3.93 | 5.78 | 5.78 | 5.60 |
| 11 | 1.53 | 1.53 | 1.48 | 3.65 | 3.68 | 3.58 | 5.65 | 5.63 | 5.70 |
| 12 | 1.50 | 1.53 | 1.38 | 3.70 | 3.85 | 3.80 | 5.90 | 5.78 | 5.65 |
| 13 | 1.78 | 1.68 | 1.65 | 3.78 | 3.78 | 3.78 | 5.83 | 5.80 | 5.68 |
| 14 | 1.75 | 1.70 | 1.70 | 3.65 | 3.68 | 3.63 | 5.72 | 5.78 | 5.72 |
| 15 | 1.60 | 1.53 | 1.55 | 3.80 | 3.78 | 3.70 | 5.65 | 5.53 | 5.65 |
| 16 | 1.50 | 1.48 | 1.50 | 3.73 | 3.73 | 3.70 | 5.68 | 5.65 | 5.68 |
| 17 | 1.55 | 1.50 | 1.58 | 3.85 | 3.85 | 3.73 | 5.55 | 5.58 | 5.63 |
| 18 | 1.60 | 1.65 | 1.53 | 3.88 | 3.80 | 3.80 | 5.65 | 5.72 | 5.58 |
| 19 | 1.53 | 1.50 | 1.48 | 3.58 | 3.58 | 3.65 | 5.58 | 5.65 | 5.60 |
| 20 | 1.53 | 1.50 | 1.48 | 3.68 | 3.70 | 3.75 | 5.60 | 5.55 | 5.53 |
| 21 | 1.50 | 1.63 | 1.50 | 3.88 | 4.03 | 3.80 | 5.75 | 5.63 | 5.78 |
| 22 | 1.38 | 1.50 | 1.38 | 3.85 | 3.75 | 3.98 | 5.90 | 5.83 | 5.88 |
| 23 | 1.65 | 1.68 | 1.60 | 3.85 | 3.70 | 3.85 | 5.65 | 5.60 | 5.65 |
| 24 | 1.65 | 1.68 | 1.73 | 3.90 | 3.83 | 3.68 | 5.65 | 5.83 | 5.85 |
| 25 | 1.45 | 1.55 | 1.43 | 3.98 | 4.05 | 4.03 | 5.88 | 5.90 | 5.85 |
| 26 | 1.43 | 1.45 | 1.50 | 3.90 | 3.90 | 3.90 | 5.72 | 5.68 | 5.72 |
| 27 | 1.58 | 1.53 | 1.55 | 3.70 | 3.73 | 3.73 | 5.65 | 5.68 | 5.63 |
| 28 | 1.65 | 1.65 | 1.65 | 3.80 | 3.78 | 3.75 | 5.65 | 5.55 | 5.60 |
| 29 | 1.40 | 1.50 | 1.50 | 3.78 | 3.78 | 3.90 | 5.70 | 5.72 | 5.72 |
| 30 | 1.50 | 1.50 | 1.50 | 3.8 | 3.73 | 3.70 | 5.83 | 5.75 | 5.78 |
| 31 | 1.75 | 1.88 | 1.65 | 3.68 | 3.7 | 3.83 | 5.65 | 5.7 | 5.60 |
| 32 | 1.68 | 1.65 | 1.63 | 3.73 | 3.83 | 3.75 | 5.83 | 5.90 | 5.85 |
| 33 | 1.70 | 1.63 | 1.60 | 3.80 | 3.83 | 3.83 | 5.78 | 5.83 | 5.80 |
| 34 | 1.65 | 1.60 | 1.63 | 3.73 | 3.78 | 3.75 | 5.78 | 5.78 | 5.78 |
| 35 | 1.68 | 1.75 | 1.65 | 3.70 | 3.70 | 3.68 | 5.65 | 5.68 | 5.66 |

Appendix H continued

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 36 | 1.50 | 1.45 | 1.60 | 3.63 | 3.60 | 3.70 | 5.65 | 5.58 | 5.65 |
| 37 | 1.45 | 1.43 | 1.43 | 3.73 | 3.75 | 3.75 | 5.50 | 5.55 | 5.47 |
| 38 | 1.45 | 1.43 | 1.48 | 3.68 | 3.68 | 3.68 | 5.63 | 5.63 | 5.47 |
| 39 | 1.78 | 1.68 | 1.65 | 3.85 | 3.78 | 4.00 | 5.90 | 5.83 | 5.78 |
| 40 | 1.73 | 1.75 | 1.70 | 3.98 | 3.95 | 3.93 | 5.90 | 5.93 | 5.83 |
| 41 | 1.60 | 1.58 | 1.55 | 3.63 | 3.58 | 3.60 | 5.40 | 5.53 | 5.50 |
| 42 | 1.48 | 1.48 | 1.55 | 3.60 | 3.58 | 3.58 | 5.50 | 5.55 | 5.60 |
| 43 | 1.63 | 1.65 | 1.58 | 3.88 | 3.88 | 3.85 | 5.75 | 5.75 | 5.72 |
| 44 | 1.50 | 1.53 | 1.50 | 3.70 | 3.75 | 3.70 | 5.65 | 5.63 | 5.65 |
| 45 | 1.83 | 1.83 | 1.78 | 3.65 | 3.73 | 3.63 | 5.58 | 5.53 | 5.55 |
| 46 | 1.85 | 1.73 | 1.68 | 3.68 | 3.70 | 3.70 | 5.55 | 5.58 | 5.53 |
| 47 | 1.58 | 1.65 | 1.63 | 3.98 | 4.03 | 3.95 | 5.95 | 5.88 | 5.90 |
| 48 | 1.50 | 1.50 | 1.53 | 4.08 | 3.90 | 3.88 | 5.40 | 5.40 | 5.38 |
| 49 | 1.55 | 1.48 | 1.65 | 3.63 | 3.63 | 3.55 | 5.30 | 5.22 | 5.25 |
| 50 | 1.58 | 1.78 | 1.50 | 3.55 | 3.58 | 4.00 | 5.13 | 5.05 | 5.10 |
| 51 | 1.48 | 1.48 | 1.48 | 3.65 | 3.63 | 3.65 | 5.13 | 5.13 | 5.10 |
| 52 | 1.50 | 1.50 | 1.50 | 3.65 | 3.73 | 3.7 | 5.25 | 5.40 | 5.33 |
| 53 | 1.38 | 1.38 | 1.45 | 3.43 | 3.45 | 3.45 | 5.53 | 5.53 | 5.47 |
| 54 | 1.40 | 1.45 | 1.50 | 3.53 | 3.45 | 3.53 | 5.58 | 5.55 | 5.58 |
| 55 | 1.80 | 1.83 | 1.75 | 3.83 | 3.80 | 3.75 | 5.78 | 5.75 | 5.78 |
| 56 | 1.73 | 1.75 | 1.75 | 3.85 | 3.73 | 3.83 | 5.83 | 5.78 | 5.78 |
| 57 | 1.48 | 1.45 | 1.55 | 3.95 | 3.98 | 4.00 | 5.75 | 5.73 | 5.83 |
| 58 | 1.50 | 1.45 | 1.45 | 3.93 | 3.88 | 4.05 | 5.65 | 5.72 | 5.78 |
| 59 | 1.78 | 1.73 | 1.63 | 3.88 | 3.85 | 3.95 | 5.85 | 5.80 | 5.72 |
| 60 | 1.73 | 1.70 | 1.65 | 3.85 | 3.83 | 3.70 | 5.78 | 5.85 | 5.80 |

*Note.* All measurements in ms

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# CURRICULUM VITA

Alexandra Gartner

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## EDUCATION

Towson University Towson, MD Projected Graduation: May 2018
**Doctor of Audiology, Au.D.**

Plattsburgh University Plattsburgh, NY May 2014
**Bachelor of Arts in Communication Disorders and Sciences; Minor in Psychology and Human Development and Family Relations**

## CLINICAL EXPERIENCE

**Bay Area Audiology,** Bel Air, MD Aug. 2016- Dec. 2016

**Hearing Assessment Center,** Lutherville and Bel Air, MD June 2016- Aug. 2016
**Private Practice** **45 Hours Direct Patient Contact**

**ENTAA Care,** Annapolis, Columbia, Glen Burnie, and Odenton MD Jan. 2016- Aug. 2016
**Ear, Nose, and Throat Clinic** **264 Hours Direct Patient Contact**

**Institute for Well-Being,** Towson MD Sept. 2014- Dec. 2015
**Towson University Hearing and Balance Center** **124 Hours Direct Patient Contact**

## ASSOCIATIONS/ COMMITTEES

Student Academy of Audiology, Vice President of Communication May 2015-May 2016
Student Academy of Audiology, Member Sept. 2014- Present
American Speech Language Hearing Association Member Aug. 2012- Dec. 2014

## VOLUNTEER EXPERIENCE

**Maryland Special Olympics**, Towson, MD June 2016
Volunteer- Healthy Athletes- Screened hearing of athletes

**Towson University Noise Monitoring**, Towson, MD April 2016, June 2016
Volunteer- Monitored the noise levels during campus wide events and concerts

**Maryland Academy of Audiology**, Annapolis, MD Oct. 2014
Volunteer- Assisted with registration and set up of a local audiology conference