The effects of high-pass masking on stimulus rate changes in the auditory brainstem response

Capstone Document

Presented in Partial Fulfillment of the Requirements for the Degree of Doctor of Audiology in the Graduate School of The Ohio State University

By

Ellen R. Hambley, B.A.

Graduate Program in Audiology

The Ohio State University

2013

Capstone Committee:

Dr. Eric C. Bielefeld, Advisor

Dr. Lawrence L. Feth

Dr. Julie L. Hazelbaker

Approved by

____

Advisor

Abstract

The auditory brainstem response (ABR) to tonal stimuli is routinely used in a clinical setting to obtain estimates of hearing sensitivity. The latency and amplitude of ABR waveforms vary with stimulus frequency, intensity, and rate. However, interactions among these stimulus parameters on the ABR have only recently been fully examined. A study measuring effects of all three stimulus parameters in the same subjects demonstrated a latency shift of ABR Wave V in response to an increase in stimulus rate that was significantly greater for low frequency, low intensity stimuli than for other stimulus conditions tested (Hess and Hood, 2012). The goal of the current study was to replicate these findings and assure frequency regions being tested were appropriately isolated through the use of a high-pass masking paradigm. The current study was designed to further evaluate the interactions among stimulus parameters on the ABR in normal hearing adults. The ABR was recorded from sixteen adults with normal hearing for eight stimulus parameter conditions. Results revealed a significantly greater rate-induced latency shift in Wave V of the ABR for the low frequency, low intensity condition, confirming the results of the Hess and Hood (2012) study. The new finding in this study was that the latencies for all conditions remained similar in relationship with the addition of high-pass masking. These results suggest a frequency effect for lower intensity signals; however, the mechanisms behind this finding remain unknown.

Acknowledgements

This research was supported by NIH/NIDCD T35-DC008763. The author would like to thank Dr. Linda Hood from the Vanderbilt University Bill Wilkerson Center for her role in the design of this study and her research laboratory facilities for the collection of the data discussed in this capstone. Thanks are extended to Dr. Lindsey Rentmeester, AuD, a current PhD student at Vanderbilt, for her assistance through the course of this study. The author also acknowledges the contributions of Dr. Eric C. Bielefeld in editing this document.

Vita

June 2007……………………………………...Hilliard Davidson High School

June 2011……………………………………...B.A. Speech and Hearing Science, The Ohio State University

2011 to 2014………………………………….Graduate Research Assistant, Department of Speech and Hearing Science, The Ohio State University

Fields of Study

Major Field: Audiology

Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction and Literature Review

Auditory brainstem response (ABR) testing is an accepted and routinely-used clinical electrophysiologic method for determining auditory function. Broadband click stimuli are routinely used in screening programs and diagnostically in assessment of neural function. Frequency specific stimuli are used in estimation of hearing sensitivity, especially in pediatric populations. Characteristics of the ABR, including peak latency, peak-to-peak amplitude, and response morphology, are affected by stimulus intensity, frequency, and rate of presentation. While numerous studies have evaluated frequency specific stimuli and the effects of stimulus intensity (Gorga, Kaminski, Beauchaine, & Jesteadt, 1988) and the effects of frequency specific stimuli and stimulus rate (Beattie, 1988; Beattie & Rochverger, 2001; Fowler & Noffsinger, 1983; Parthasarathy, Borgsmiller, & Cohlan, 1998), few studies have looked at all three parameters of stimulus frequency, intensity, and rate in combination. Studies using click stimuli in adults have suggested that latency shifts due to the stimulus parameters of stimulus intensity and stimulus rate are independent of each other (Don, Allen, & Starr, 1977); however, these parameters may not be independent of each other when other factors such as frequency and age are considered (Fowler & Noffsinger, 1983; Parthasarathy, Borgsmiller, & Cohlan, 1998).

Based on the lack of information where all three stimulus parameters of frequency, intensity, and rate were directly compared in the same listeners, Hess and Hood (2012) completed a study of young adults with normal hearing as a baseline study for future research that would explore neural changes with aging. An unexpected finding from the Hess and Hood (2012) study was a significantly greater latency shift of Wave V of the ABR with increased stimulus rate for the low frequency and low intensity stimulus condition than for the other stimulus conditions tested. The mechanisms behind this greater rate-induced Wave V latency shift remain unknown.

The primary aim of the present study was to confirm the frequency specific nature of the Hess and Hood (2102) finding by limiting the frequency regions being tested through the use of a high-pass masking paradigm. The secondary aim was to complete a follow-up study that would confirm replicability of the previous findings. It was hypothesized that the larger rate-induced Wave V latency shift would be present for the low frequency, low intensity stimuli both without the presence of the high-pass masker, confirming the previous study results, and with the high-pass masker present, confirming the frequency specificity of the previous study.

Auditory Brainstem Response

The auditory brainstem response is an evoked potential generated by the collective response of onset-sensitive neurons along the eighth cranial nerve and auditory brainstem pathway, recorded from electrodes placed on the scalp. An auditory stimulus is presented and the resulting waveform generally consists of five to seven waves with predictable latencies. Stimulus properties, including frequency, intensity, and rate, have notable effects on latency and amplitude of the ABR waveform (Stapells & Oates, 1997). Considerable research exists on the effects of isolated stimulus parameters on the ABR (Parthasarathy, Borgsmiller, & Cohlan, 1998; Don, Allen, & Starr, 1977; Gorga, et al., 1988; Weber & Fujikawa, 1977); however, few studies have examined the effects and interactions of all three stimulus characteristics of frequency, intensity, and rate on the ABR in the same population. For the purposes of the current study, the following review is focused on the effects of stimulus parameters on Wave V of the ABR.

Frequency Effects

The effects of stimulus frequency on the ABR have been well-examined in the normal hearing population. Gorga et al. (1988) measured the ABR in 20 normal hearing subjects in response to a range of stimulus frequencies from 250 to 8000 Hz in order to describe the changes in waveform characteristics with changes in stimulus frequency. The resulting data demonstrated that ABR waveforms were more reproducible in response to high frequency stimuli than for low frequency stimuli. As stimulus frequency decreased, peaks in the ABR waveform broadened and became less distinct. This observation is likely related to several factors that affect the amplitude of the response in comparison to the background noise. High frequency stimuli have a more rapid rise time, resulting in greater neuron discharge synchrony and higher response amplitude. In addition, the basal end of the cochlea displays a higher nerve fiber density (Spoendlin, 1972), which could result in a greater number of neurons firing in synchrony in response to high frequency stimuli. Therefore, with increasing stimulus frequency, neural firing becomes more synchronous and occurs in a greater population of neurons, resulting in more reproducible ABR waveforms (Gorga et al., 1988).

Further, Gorga et al. (1988) observed increases in ABR waveform latency with decreases in stimulus frequency. This increase in latency may be due, in part, to differences in stimulus rise time. A longer stimulus rise time is typically used with lower frequency stimuli, which could result in increased response latency. Importantly, the point of maximum excitation along the basilar membrane of the cochlea shifts toward the apex as stimulus frequency is decreased, which causes an increase in response latency. Therefore, due to the longer stimulus rise time and the location of cochlear excitation, ABR waveform latency increases as stimulus frequency decreases (Gorga et al., 1988).

Similar results were measured by Parthasarathy, Borgsmiller, and Cohlan (1998) in a study examining the ABR in response to stimulus frequencies of 250 and 2000 Hz. Ten normal hearing adults and ten normal hearing neonates were subjects in this study and in both populations, there was an increase in ABR Wave V latency with a decrease in stimulus frequency from 2000 Hz to 250 Hz. The latency shift observed as a result of the change in stimulus frequency was significant for both the neonatal and adult populations (Parthasarathy, Borgsmiller, & Cohlan, 1998).

Intensity Effects

Numerous investigations of the ABR have examined the effects of stimulus intensity on the resulting waveform. Research demonstrates that both latency and amplitude of ABR waveforms are impacted by stimulus intensity. Weber and Fujikawa (1977) measured the ABR in 22 normal hearing adults at seven intensity levels from 10 to 60 dB sensation level (SL) to determine latency information for varying stimulus intensities. The results demonstrated a clear reduction in ABR Wave V latency with increased stimulus intensity. This reduction in latency may be a result of basal spread of excitation that occurs with increased stimulus intensity. Presentation of high intensity stimuli also results in firing of more neural fibers in comparison to low intensity stimuli, possibly leading to more rapid onset of neuronal action potentials (Weber & Fujikawa, 1977). Similar results were observed by Gorga et al. (1988) using stimulus intensity levels varying from 20 to 100 dB SPL. Twenty normal hearing subjects were included in the study and the resulting ABR waveforms demonstrated a decrease in absolute Wave V latency with increased stimulus intensity (Gorga et al., 1988).

Rate Effects

Several studies have addressed the effects of stimulus rate on the ABR and results show that both waveform latency and amplitude are impacted by varying stimulus rate. Parthasarathy, Borgsmiller, and Cohlan (1998) measured the ABR in 10 normal hearing adults and 10 normal hearing neonates at stimulus rates of 11.1 and 55.5 per second using 250 and 2000 Hz tonebursts at 75 dB nHL, in an effort to examine changes in the ABR with differing stimulus rates. Increasing the stimulus rate from 11.1 to 55.5 stimulus presentations per second resulted in prolonged absolute latency of Wave V in both adults and neonates at both stimulus frequencies. The measured rate-induced latency shift was similar in magnitude across the two stimulus frequency conditions. Statistical analysis revealed no significant rate by frequency interaction. The rate-induced increase in latency demonstrated in this study may be a result of neural fatigue and adaptation that can occur in response to higher stimulus rates. Additionally, an increased stimulation rate may lead to dys-synchrony in neural firing, which would result in prolonged latency. Parthasarathy, Borgsmiller, and Cohlan (1998) measured that this increase in latency with a higher stimulus rate was significantly greater in neonates than adults. This is likely due to the immature development of the central auditory nervous system at birth (Parthasarathy, Borgsmiller, & Cohlan, 1998).

Similar results were observed by Don, Allen, and Starr (1977) in a study of six normal hearing subjects. The ABR was measured at increasing click stimulus rates of 10, 30, 50, and 100 per second and a clear latency shift was observed with increased stimulus presentation rate. A mean Wave V latency shift of 0.5 milliseconds was measured in comparing the ABR obtained with a stimulus rate of 10 per second to that with a stimulus rate of 100 per second (Don, Allen, & Starr, 1977). Likewise, Weber and Fujikawa (1977) measured the ABR in 22 normal hearing adults at three different click stimulus rates of 13.3, 33.3, and 67 per second and found that absolute Wave V latency increased as stimulus rate increased. In addition, the resulting waveforms demonstrated reduced amplitude and poorer clarity with increased stimulus rate. As the stimulus rate is increased, neural fatigue and adaptation likely result, leading to reduced neural firing and subsequently reduced amplitude of the ABR (Weber & Fujikawa, 1977).

Interactions of Stimulus Frequency, Intensity, and Rate

Though the effects of stimulus frequency, intensity, and rate on the ABR have been examined and defined individually and, in some cases, in combination, there is a lack of information on the effects and interactions of all three of these stimulus parameters in combination in the same population. All of the aforementioned studies examined no more than two of these parameters. In studies examining the effects of stimulus rate and intensity (Weber & Fujikawa, 1977; Don, Allen, & Starr, 1977), stimulus frequency was invariable because click stimuli were employed in all conditions. In examinations of stimulus frequency and intensity (Gorga, et al., 1988), stimulus rate was kept constant and therefore eliminated as a variable. In studies of varying stimulus rate and frequency (Parthasarathy, Borgsmiller, & Cohlan, 1998), all stimuli were presented at the same intensity. The interactions of stimulus frequency, intensity, and rate and the subsequent effects on the ABR have not been thoroughly examined and are not well-defined at this point.

Based on the lack of research measuring combinations of all three stimulus dimensions in the same individuals, Hess and Hood (2012) measured the ABR in 10 normal hearing adults at varying frequencies (1500 and 6000 Hz), intensities (45 and 75 dB nHL), and rates (27.7 and 77.7 per second). The ABR was also measured using click stimuli (at 35 and 75 dB nHL) in these same individuals for comparison to previous studies that employed click stimuli. The resulting waveforms demonstrated increased Wave V latency as a result of decreased stimulus frequency, decreased stimulus intensity, and increased stimulus rate, consistent with the existing literature. The key new finding was that the magnitude of latency shift measured with increased stimulus rate was dependent upon both stimulus frequency and intensity. A significantly greater rate-induced Wave V latency shift was measured for one condition compared to all other conditions. For the lower frequency toneburst (1500 Hz) at the lower intensity (45 dB nHL), the Wave V latency shift of 0.577 msec that occurred in response to increasing the stimulus rate from 27.7 to 77.7 per second was significantly greater than the rate-induced latency shift measured in any other condition. Although there was not a clear explanation for this finding, it was noted that the 1500 Hz toneburst at the lower intensity of 45 dB nHL differed from the other stimuli used in the study, as it was likely stimulating a more apical region of the cochlea with less spread of excitation to the basal region than for the higher intensity, low frequency stimulus. This was hypothesized as the reason that a similar rate-induced Wave V latency shift was not observed for the higher intensity (75 dB nHL), low frequency (1500 Hz) toneburst. Perhaps the latency did not shift to the same degree in the higher intensity (75 dB nHL), lower frequency (1500 Hz) condition due to the likely basal spread of excitation that occurs with increased stimulus intensity. This finding brought into question the frequency specificity of the stimuli and required that further research address the combination of these same stimulus parameters of frequency, intensity, and rate, while ensuring frequency specificity of the stimuli.

A proposed and commonly used method of isolating a specific frequency region in recording the ABR involves the use of a high-pass masking paradigm (Oates & Stapells, 1997). In order to determine whether this unexpected rate-induced Wave V latency increase was truly both a frequency and intensity effect, the current research project focused on controlling the frequency specificity of the stimuli, through the use of high-pass masking.

High-Pass Masking

Numerous methods of noise masking have been employed in determining frequency specificity of the ABR in response to different stimuli. Some of these methods include pure-tone masking (Mackersie, Down, & Stapells, 1993; Wu & Stapells, 1994), notched-noise masking (Picton, Ouellette, Hamel, & Smith, 1979; Stapells & Picton, 1981), and high-pass noise masking (Don & Eggermont, 1978; Eggermont & Don, 1980; Nousak & Stapells, 1992). Studies have demonstrated that, of these types of masking, high-pass noise masking results in the most frequency specific response, since it produces minimal downward spread of masking (Stapells, Picton, & Durieux-Smith, 1994). The use of high-pass noise masking to ensure frequency specificity of the ABR response has been proposed based on a small number of studies suggesting poor frequency specificity of the ABR to high intensity unmasked low frequency tonal stimuli. These studies propose that the ABR response to high intensity low frequency tones is primarily generated from the basal portion of the cochlea, due to basal spread of excitation (Davis & Hirsch, 1976; Laukli, 1983a, 1983b). Contrary to these results, Oates and Stapells (1997) investigated the frequency specificity of the ABR in response to 500 and 2000 Hz tonebursts using high-pass masking. The ABR was measured in 12 normal hearing adults in response to stimuli at 500 and 2000 Hz in quiet, broadband noise, and high-pass masking noise at nine different cutoff frequencies. The resulting waveforms demonstrated little to no change until the cutoff frequency of the masking noise was within half an octave of the nominal frequency of the stimulus. These results indicated that there was little contribution of stimulus energy from frequencies greater than one octave above the stimulus frequency for 500 and 2000 Hz tonebursts. However, based on the mixed findings of studies on the frequency specificity of the ABR in response to high intensity low frequency tonal stimuli, the present study was designed to include conditions with and without high-pass masking noise to further examine basal contributions to the ABR response in the high intensity, low frequency condition.

The Present Study

There does not appear to be conclusive evidence regarding the specific effects and interactions of stimulus frequency, intensity, and rate on the ABR. The limited research that exists demonstrates a greater rate-induced latency shift of Wave V in the low frequency, low intensity stimulus condition. This rate-induced latency shift appears to be both a frequency and intensity effect, due to the lack of a similarly long latency shift in the low frequency, high intensity stimulus condition (Hess & Hood, 2012). The purpose of the present study was to determine if the previously observed results are replicable and if they will remain consistent when the frequency regions tested are isolated by adding high-pass masking noise.

Chapter 2: Methods

Prior to the main study, a pilot study was completed. The reason for the pilot study was to determine the appropriate levels of high-pass masking noise to be applied in each of the masked stimulus conditions in the main study. The pilot study was necessary to measure the levels of masking noise required to effectively mask basal contributions of the cochlea while maintaining a measurable ABR waveform.

Pilot Study Subjects

Five ears (two right ears, three left ears) were tested in five normal hearing individuals (four females, one male, age 22-30 years, mean age 25.33 years). All subjects were considered to have normal hearing based on pure-tone air-conduction thresholds <20 dB HL across the frequency range from 250 to 8000 Hz, present distortion product otoacoustic emissions (DPOAEs) for stimuli presented at L1=65, L2=55 dB SPL, normal tympanograms (peak pressure -150 to 50 mmhos, static compliance 0.3 to 1.5 cc, equivalent ear canal volume 0.5 to 2.0 cc), and present ipsilateral and contralateral middle ear muscle reflexes at 500, 1000, and 2000 Hz. This study was approved by the Vanderbilt University Institutional Review Board. Subjects were compensated for their participation according to Vanderbilt IRB approved guidelines.

Pilot Study Procedure

The purpose of the pilot study was to determine the levels of broadband noise necessary to mask the toneburst stimuli to be used in the present study (1500 and 6000 Hz tonebursts, at 75 and 45 dB nHL, at rates of 27.7 and 77.7 per second). Determining the broadband noise masking thresholds for each of the toneburst stimuli was required in order to decide upon appropriate presentation levels for the high-pass masking noise to be employed in the current study. The appropriate masking noise levels would provide masking of any high frequency response without resulting in complete masking of the auditory brainstem response. The pilot study was also necessary in order to confirm similarity of masking thresholds across pilot study participants. Measuring similar masking thresholds across pilot study participants would justify use of a single masking level for each stimulus condition in the following study, rather than measurement of individual masking thresholds for each participant in the main study.

Behavioral broadband noise masking thresholds were measured in one ear of each of the five pilot study participants. Toneburst stimuli and broadband masking noise were presented simultaneously, beginning at a signal-to-noise ratio (35 dB SNR) at which the toneburst stimuli were clearly perceived above the broadband masking noise. The broadband masking noise was subsequently increased in 5 dB steps until the participant behaviorally reported that the toneburst stimulus was no longer heard. After behavioral masking thresholds were measured for each of the toneburst stimuli, electrophysiologic masking thresholds were measured for the same toneburst stimuli. Toneburst stimuli and broadband masking noise were presented simultaneously to the same ear that was used for behavioral masking threshold measurements. Broadband masking noise was initially presented at a level 20 dB below the behavioral masking threshold for that individual participant for the particular toneburst stimulus and was subsequently increased in 10 dB increments until the auditory brainstem response was no longer measureable. These electrophysiologic masking thresholds were then compared to the behavioral masking thresholds. Based on the good agreement between behavioral and electrophysiologic masking thresholds for each individual participant (within 10 dB), and good agreement in masking thresholds across participants (within 15 dB), the electrophysiologic masking thresholds were averaged across participants. The average electrophysiologic broadband noise masking levels across participants were then used to set the levels of the high pass masking noise for the current study (Oates & Stapells, 1997). High-pass masking noise levels used in the main study can be found in Table 1.

Main Study Subjects

Sixteen ears (eight right ears, eight left ears) were tested in sixteen normal hearing individuals (14 females, 2 males, age 22-33 years, mean age 26.47 years). The number of test participants was determined by a power analysis completed prior to data collection. All subjects were determined to have normal hearing based on a series of baseline screening procedures, which included pure-tone air conduction audiometry, DPOAEs for stimuli presented at L1=65, L2=55 dB SPL, tympanometry, and ipsilateral and contralateral middle ear muscle reflexes. A status of normal hearing denoted pure-tone air-conduction thresholds <20 dB HL across the frequency range from 250 to 8000 Hz, present DPOAEs with ≥6 dB signal-to-noise ratio, normal tympanograms (peak pressure -150 to 50 mmhos, static compliance 0.3 to 1.5 cc, equivalent ear canal volume 0.5 to 2.0 cc), and present ipsilateral and contralateral middle ear muscle reflexes at 500, 1000, and 2000 Hz.

Demographic information including ages for all subjects can be found in Table 2. Subjects were compensated for their participation according to approved guidelines. This study was approved by the Vanderbilt University Institutional Review Board.

ABR Stimulus Parameters

ABR stimulus parameters used in the present study followed those used in a previous study (Hess & Hood, 2012). Briefly, Hess & Hood (2012) selected two stimulus frequencies (1500 Hz and 6000 Hz), two intensities (45 dB nHL and 75 dB nHL), and two rates (27.7 per second and 77.7 per second). The 1500 and 6000 Hz tonebursts were chosen to target lower and higher frequency regions. 1500 Hz was selected as the low frequency stimulus in order to still allow for reasonably precise waveform peak identification, as ABR waveforms in response to stimulus frequencies below 1500 Hz typically display poorer morphology and less distinct response peaks (Gorga, et al., 1988). The 1500 Hz stimulus was presented with a 3 ms rise/fall time and the 6000 Hz stimulus was presented with a 2 ms rise/fall time. Intensity levels of 45 and 75 dB nHL were selected to include a higher intensity (75 dB nHL) and a lower intensity (45 dB nHL) nearer to threshold that still allowed for identification of response peaks. Rates of 27.7 and 77.7 per second were chosen to include a slower rate and a faster rate, and for comparison to previous literature detailing rate effects for stimulus rates below 30 per second and above 60 per second (Don, Allen, & Starr, 1977). In the present study, these previous stimulus parameters were replicated and additionally, each stimulus condition was presented with and without high-pass masking noise. Presentation order of test conditions was counterbalanced across subjects. Stimulus conditions can be found in Table 3.

High-pass Masking Noise Characteristics and Calibration

High-pass masking noise utilized in the current study was digitally created with high-pass cutoffs of 2121 Hz for the lower frequency toneburst and 8485 Hz for the higher frequency toneburst. The specific cutoff frequencies were selected in an effort to mask any contribution from frequencies above the target frequencies for the lower (1500 Hz) and higher frequency (6000 Hz) tonebursts. Based on previous high-pass masking studies, ABR responses remain largely unchanged as the cutoff frequency of high-pass masking noise is lowered until the cutoff frequency is within one-half octave of the target stimulus frequency. Once the cutoff frequency reaches one-half octave above the target stimulus frequency, a significant decrease in amplitude and increase in latency of the ABR is observed (Oates & Stapells, 1997). For the current study, the high-pass masking noise was designed to mask any response from frequencies above the target stimulus frequency without resulting in significant deterioration of a measurable ABR waveform. Therefore, cutoff frequencies of 2121 Hz and 8485 Hz were selected for the high-pass masking noise to be utilized with the 1500 Hz and 6000 Hz toneburst stimuli, respectively. The high-pass masking stimuli were filtered with an eight-pole Butterworth filter, with a slope in excess of 96 dB per octave. This form of filtering is consistent with filtering processes commonly used in frequency-specific ABR studies with high-pass maskers and notched noise maskers (Don & Eggermont, 1978; Kavanagh, Harker, & Tyler, 1984; Oxenham & Simonson, 2009). Calibration was completed for each stimulus type via the test earphone using a Bruel & Kjaer (B&K) Pulse calibration system (software version 11.0; Norcross, GA, USA) coupled through a B&K Type 4157 Ear Simulator. This calibration system has a "peak hold" capability, allowing calibration in peak sound pressure levels (peak SPL) for brief toneburst stimuli.

Procedure

All subjects were tested using a two-channel electrode montage, allowing for recording from the ipsilateral and midline channels simultaneously. The rationale for including the midline montage was based on higher amplitudes for Wave V reported for the midline over ipsilateral montage. The ipsilateral montage consisted of the non-inverting electrode placed at the vertex (C_z) and the inverting electrode placed on one earlobe (A_1 or A_2, depending on the test ear). The midline montage employed the non-inverting electrode placed at the vertex (C_z) and the inverting electrode at the nape of the neck (C_7). The ground electrode was placed on the forehead (F_{pz}). Responses were filtered from 100 to 3000 Hz and two averages of 4096 sweeps were obtained for each stimulus condition. Artifact rejection was set to +/- 15.5 microvolts.

All ABR testing was conducted using the Intelligent Hearing Systems (Miami, FL) Smart EP system. Use of the Advanced Research Module was required for testing, in order to present toneburst stimuli and high-pass masking noise simultaneously through the same insert earphone. ABR-eliciting stimuli and high-pass masking noise were presented to one ear through a Type 3A insert earphone, while the non-test ear was plugged with a foam earplug. All testing was conducted in a double-walled sound treated room. Subjects reclined comfortably in a lounge chair and either slept or sat quietly to minimize movement. Each participant sat for approximately two to three hours of testing conducted in one test session. Breaks were taken when needed, according to subject preferences.

Waveform Analysis

Following data collection, positive Wave V peak and negative Wave V' trough was identified for all waveforms and measurements were made for the dependent variable of Wave V absolute latency. It was expected that Wave V would be present in most conditions for most participants given its robustness, consistent with previous research that noted overall presence of Wave V for the current study conditions (Hess and Hood, 2012). Each peak identification measurement was made by the primary investigator (PI) and by two additional observers experienced in ABR analysis. All three persons were blind to the test condition during review of the waveforms for each participant. These reviews were completed independently by each reviewer, and then discussed among the three reviewers. If peaks were determined to be present and in the same location by two of the three reviewers, the identification and associated values were accepted. Any markings not reaching these criteria were discussed and a consensus reached. After the blind review and consensus, responses were reviewed again for each condition across participants with latency values of marked waveforms made available to the reviewers. Additional reviews for outliers were completed during the analysis process for peak latency. For the dependent variable, all individual responses were plotted in a scatterplot for each condition. Additionally, the ranges of one and two standard deviations for each condition were identified and values that were outside these ranges were reviewed. Any outliers that were not clustered with the group in the scatterplots or that were outside the range of one and two standard deviations, resulted in a re-review of the individual waveform and notes documented during recording. Based on this re-review, a number of Wave V and V' identifications were adjusted based upon agreement among all three reviewers. The subsequent Wave V latency measurements were utilized in data analysis.

Statistical Analysis

Statistical analysis included a 5-way repeated measures analysis of variance (ANOVA) to evaluate the main effects of electrode montage (2 levels), stimulus frequency (2 levels), stimulus intensity (2 levels), repetition rate (2 levels), and presence of masking (2 levels), on absolute Wave V latency. A separate 4-way repeated measures ANOVA was completed testing the main effects of electrode montage (2 levels), stimulus frequency (2 levels), stimulus intensity (2 levels), and presence of masking (2 levels) on rate-induced Wave V latency shift.

Table 1. High-pass masking noise levels (in dB nHL).

Stimulus Frequency	High Intensity (75 dB nHL)	Low Intensity (45 dB nHL)
1500 Hz	60	30
6000 Hz	70	45

Table 2. Subject demographic information.

Subject	Ear	Age (years, months)	Gender
P1	L	23,11	F
P2	R	22,10	F
P3	L	26,2	M
P4	R	25,10	F
P5	L	24,11	F
P6	R	26,1	F
P7	L	23,11	F
P8	R	22,3	F
P9	R	24,7	F
P10	L	24,3	F
P11	R	28,8	F
P12	L	30,0	M
P13	R	27,3	F
P14	L	32,8	F
P15	R	27,0	F
P16	L	33,2	F

Table 3. Test conditions completed on each participant.

	Stimulus Rate	
Stimulus Frequency	27.7	77.7
1500 Hz	45 dB nHL	45 dB nHL
	75 dB nHL	75 dB nHL
6000 Hz	45 dB nHL	45 dB nHL
	75 dB nHL	75 dB nHL

* Test order was counterbalanced across participants. Each test condition was presented four times (twice with high-pass masking, twice without high-pass masking). For subjects P1-P8, each condition was presented in the following order: (1) without noise, (2) with noise, (3) without noise, (4) with noise. For subjects P9-P16, each condition was presented in the following order: (1) with noise, (2) without noise, (3) with noise, (4) without noise.

Chapter 3: Results

The primary purpose of this study was to apply high-pass masking to the previous study's stimulus conditions to determine if previous findings were appropriately isolated to low and high frequency regions. The secondary purpose was to replicate the findings of the previous study. Figure 1 displays representative ABR waveforms for one subject. Each displayed waveform represents the summed waveform of two replications for the particular stimulus condition. Criteria for replicable waveforms included Wave V latency within one-tenth of a millisecond and general qualitative similarities in waveform morphology. In some cases, three repetitions of a particular stimulus condition were completed and the two most replicable waveforms were selected according to approved criteria. In Figure 1, waveforms are presented for the different stimulus intensity levels (45 and 75 dB nHL) and stimulus rates (27.7 and 77.7 per second) for the frequencies of 1500 and 6000 Hz in both the unmasked and masked conditions. The positive peak identified as Wave V and negative trough identified as Wave V' are indicated on each waveform. It is clear that Wave V can be identified across the different stimulus conditions. While some variability existed in waveforms between subjects, the overall morphology of the ABR waveforms was comparable across all sixteen subjects.

Figure 2 displays the mean absolute Wave V latency for all stimulus conditions measured from the ipsilateral channel with high intensity stimuli displayed on the left panel and low intensity stimuli displayed on the right panel. Additionally, mean absolute Wave V latency values and standard deviations measured from the ipsilateral channel can be found in Table 4. Prior to completing statistical analysis of data for the current study, individual mean absolute Wave V latencies were plotted for all subjects for each stimulus condition and examined for outliers. Standard deviations were calculated for each condition and Wave V latency values that exceeded one or two standard deviations above or below the mean were identified. Waveforms for all outliers exceeding one or two standard deviations above or below the mean were re-examined for agreement on appropriate Wave V placement and a number of Wave V identifications were adjusted upon agreement between all waveform reviewers. After examination and agreement upon accuracy of outliers, 5-way repeated measures ANOVA was used to evaluate the main effects of electrode montage, stimulus frequency, intensity, repetition rate, and high-pass masking on absolute Wave V latency. Results revealed no significant main effect of channel on mean absolute Wave V latency. Due to the lack of significant difference between mean absolute Wave V latency measured from the ipsilateral and midline channels, ipsilateral channel data were selected for comparison purposes. This decision was made based on the use of ipsilateral channel data for analysis of latency shifts in the previous study (Hess & Hood, 2012).

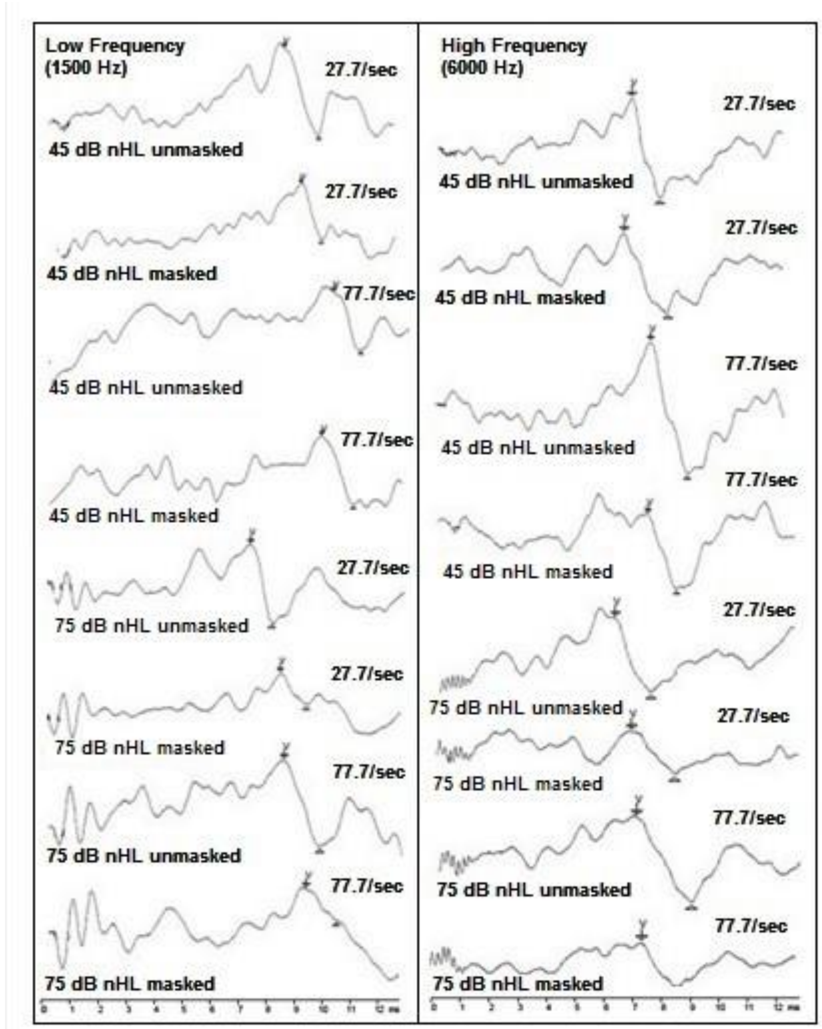

Figure 1. ABR waveforms for one subject. Waveforms in response to 1500 Hz tonebursts (left panel) and 6000 Hz tonebursts (right panel).

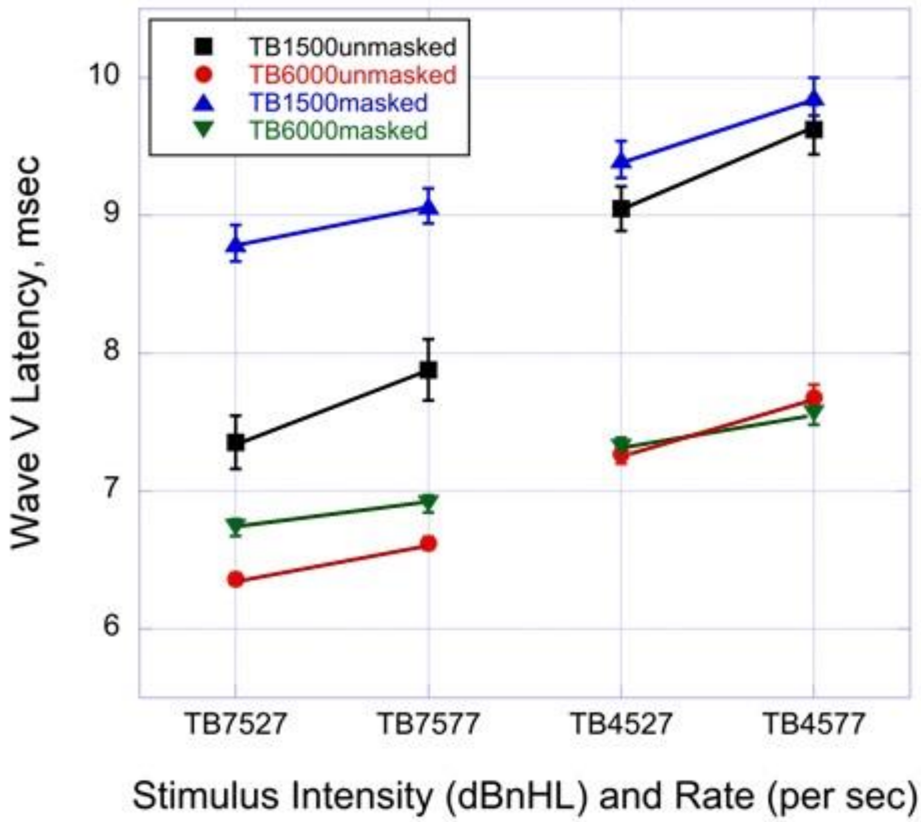

Figure 2. Mean absolute Wave V latency measured from the ipsilateral channel for all stimulus conditions: low frequency unmasked tonebursts (black squares), high frequency unmasked tonebursts (red circles), low frequency masked tonebursts (blue triangles), and high frequency masked tonebursts (green triangles). Wave V latency in response to high intensity stimuli (left panel) and Wave V latency in response to low intensity stimuli (right panel) are displayed. Within each panel, Wave V latency in response to slow rate (left) and Wave V latency in response to fast rate (right) is displayed. Rate-induced Wave V latency shift is represented by the connection between data points within each panel.

Table 4. Mean absolute Wave V latency and SD (in msec).

Stimulus Frequency	Rate		Wave V			
			High Intensity		Low Intensity	
			Unmasked	Masked	Unmasked	Masked
1500 Hz	27.7/sec	Mean	7.23	8.80	9.05	9.41
		SD	0.35	0.53	0.65	0.54
		n	16	16	16	16
	77.7/sec	Mean	7.61	9.07	9.62	9.86
		SD	0.33	0.51	0.72	0.55
		n	16	16	16	16
6000 Hz	27.7/sec	Mean	6.36	6.73	7.27	7.32
		SD	0.18	0.24	0.28	0.28
		n	16	16	16	16
	77.7/sec	Mean	6.62	6.90	7.68	7.56
		SD	0.18	0.25	0.37	0.33
		n	16	16	16	16

Additionally, this repeated-measures ANOVA indicated significant main effects of stimulus frequency ($F(1, 15) = 295.69$, $p<0.001$), level ($F(1,15) = 234.18$, $p<0.001$), rate ($F(1,15) = 136.17$, $p<0.001$), and masking ($F(1,15) = 294.46$, $p<0.001$) on absolute Wave V latency. Analysis revealed that increased stimulus frequency resulted in significantly shorter Wave V latency. In addition, increased stimulus intensity also resulted in significantly shorter Wave V latency, while increased stimulus rate resulted in significantly longer Wave V latency. Also, addition of high-pass masking resulted in significantly longer Wave V latency in comparison to Wave V latency measured in response to unmasked stimuli. Statistical values for the 5-way repeated measures ANOVA can be found in Table 5.

This repeated measures ANOVA also showed several significant two-way interactions between stimulus parameters. The interaction of stimulus frequency by stimulus level was significant ($F(1,15) = 19.18$, $p<0.001$). Analysis of this interaction demonstrated a significantly greater shift in Wave V latency with an increase in stimulus intensity for the low frequency condition (1500 Hz) than the high frequency condition (6000 Hz). The interaction of stimulus frequency by stimulus rate was also significant ($F(1,15) = 5.60$, $p<0.05$). Analysis of this interaction revealed a significantly greater shift in Wave V latency with increased stimulus rate for low frequency than high frequency stimuli. While statistically significant within the parameters that were studied, these effects were fairly subtle.

The interaction of stimulus level by stimulus rate was also significant ($F(1,15) = 4.90$, $p<0.05$). Analysis of this interaction revealed significantly greater shift in latency with increased stimulus rate for lower level stimuli than higher level stimuli. The increase in stimulus rate may have a greater impact in low level stimulus conditions because a narrower cochlear region is likely activated in response to the lower level stimulus. In addition, the interaction of stimulus frequency by masking was significant ($F(1,15) = 183.98$, $p<0.001$). Analysis of this interaction revealed a significantly greater shift in Wave V latency for the low frequency condition (1500 Hz) when high-pass masking was introduced than for the high frequency condition (6000 Hz).

Also, the interaction of stimulus level by masking was significant ($F(1, 15) = 215.75$, $p<0.001$). Analysis of this interaction demonstrated significantly greater shift in Wave V latency with addition of masking for higher intensity than lower intensity stimulus conditions. At higher stimulus intensities, the target signal envelope is broader; therefore, addition of high-pass masking has a greater effect than at lower stimulus intensities. The interaction of stimulus rate by masking was also significant ($F(1,15) = 9.11$, $p<0.05$). Analysis of this interaction showed a significantly greater effect of masking on Wave V latency for the slower rate condition than the faster rate condition. The reason behind this finding is unknown at present.

The interaction of stimulus frequency by stimulus level by masking was also significant ($F(1,15) = 58.48$, $p<0.001$). Analysis of this interaction demonstrated a greater shift in Wave V latency with addition of masking for the low frequency, high intensity stimulus condition than for any other stimulus condition. Addition of high-pass masking resulted in increased Wave V latency almost universally across all stimulus conditions; however, the measured increase in latency for the 1500 Hz toneburst at 75 dB was significantly greater than for any other condition. The difference in Wave V latency with addition of high-pass masking between low and high frequency conditions may have been influenced by possible spectral differences between the low and high frequency tonebursts. Additionally, between the two low frequency toneburst conditions, presence of high-pass masking would be expected to have a greater effect on the higher level toneburst than the lower level toneburst, based on the broader signal envelope of a higher intensity toneburst. Therefore, the significant interaction between stimulus frequency, stimulus level, and masking shows that addition of masking had a significantly greater effect on Wave V latency for the low frequency, high intensity stimulus condition than the other stimulus conditions in the current study.

Figure 3 displays the mean rate-induced Wave V latency shift observed between the unmasked conditions in the current study and the previous study. Error bars indicate one standard error above the mean. Mean rate-induced latency shift and standard deviation values between the unmasked conditions of the current study and the previous study can be found in Table 6. Results from the current study in the unmasked condition were comparable to results from the previous study.

Figure 4 displays the mean rate-induced Wave V latency shift observed between the unmasked and masked conditions in the current study. Error bars indicate one standard error above the mean. Mean rate-induced Wave V latency shift and standard deviation values for all conditions can be found in Table 7. A separate 4-way repeated-measures ANOVA revealed a significant main effect of stimulus frequency ($F(1, 15) = 6.43$, $p<0.05$) and masking ($F(1,15) = 22.21$, $p<0.001$) on rate-induced Wave V latency shift. There were no significant interactions between stimulus parameters in the case of Wave V latency shift. Analysis of the main effects revealed that for the unmasked conditions, mean rate-induced Wave V latency shift was greater for the low frequency stimulus conditions than the high frequency stimulus conditions. In addition, the same effect was observed for masked conditions. Mean Wave V latency shift for masked low frequency conditions was greater than for masked high frequency conditions. Analysis also revealed that addition of high-pass masking resulted in a reduction in rate-induced Wave V latency shift across all stimulus conditions. Statistical values for the 4-way repeated measures ANOVA can be found in Table 8.

Table 5. Repeated measures ANOVA results for the dependent variable Wave V latency

Main Effect	MS	df	F	p
A. Stimulus Frequency	401.97	1	295.69	<0.001
B. Stimulus Intensity	143.80	1	234.18	<0.001
C. Stimulus Rate	15.62	1	136.17	<0.001
D. High-pass Masking	37.77	1	294.46	<0.001
E. Electrode Montage	0.113	1	4.216	n.s.
Two-way Interactions				
A x B	7.63	1	19.18	<0.001
A x C	0.68	1	5.60	<0.05
B x C	0.51	1	4.90	<0.05
A x D	19.25	1	183.98	<0.001
B x D	19.69	1	215.75	<0.001
C x D	0.61	1	9.109	<0.05
Three-way interactions				
A x B x D	7.03	1	58.48	<0.001

MS = Mean Square, df = degrees of freedom, F = F-Statistic Value, p = significance.

Table 6. Mean Wave V latency shift comparison between previous and current studies.

Stimulus Frequency	Rate Comparison		High Intensity		Low Intensity	
			Current Study	Hess & Hood	Current Study	Hess & Hood
1500 Hz	77.7/sec-27.7/sec	Mean (in msec)	0.38	0.30	0.57	0.58
		SD (in msec)	0.34	0.21	0.63	0.17
		n	16	10	16	10
6000 Hz	77.7/sec-27.7/sec	Mean (in msec)	0.26	0.29	0.41	0.38
		SD (in msec)	0.17	0.10	0.24	0.12
		n	16	10	16	10

Table 7. Mean Wave V latency shift unmasked vs. masked conditions of current study.

Stimulus Frequency	Rate Comparison		High Intensity		Low Intensity	
			Unmasked	Masked	Unmasked	Masked
1500 Hz	77.7/sec-27.7/sec	Mean (in msec)	0.38	0.27	0.57	0.46
		SD (in msec)	0.34	0.42	0.63	0.28
		n	16	16	16	16
6000 Hz	77.7/sec-27.7/sec	Mean (in msec)	0.26	0.17	0.41	0.24
		SD (in msec)	0.17	0.29	0.24	0.18
		n	16	16	16	16

Table 8. Repeated measures ANOVA results for the dependent variable Wave V latency-rate shift comparing stimulus frequency, intensity, masking, and electrode montage.

Main Effect	MS	df	F	p
A. Stimulus Frequency	2.42	1	6.43	<0.05
B. Stimulus Intensity	0.42	1	0.93	n.s.
C. High-pass Masking	1.86	1	22.21	<0.001
D. Electrode Montage	0.00	1	0.07	n.s.

MS = Mean Square, df = degrees of freedom, F = F-Statistic Value, p = significance.

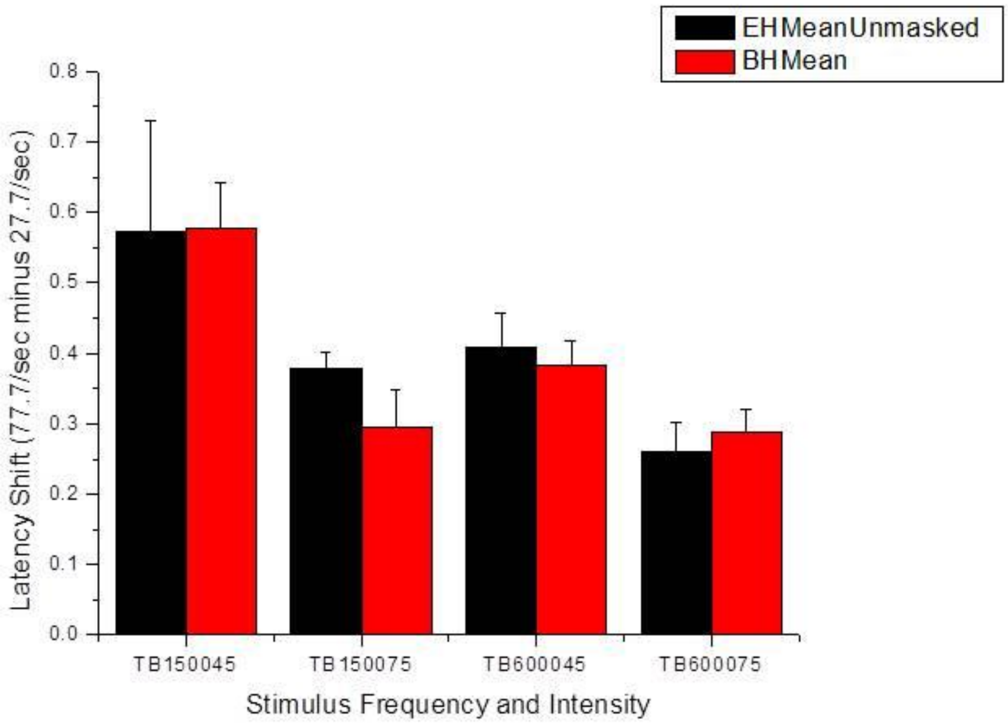

Figure 3. Mean rate-induced Wave V latency shift observed (with an increase in stimulus rate from 27.7/sec to 77.7/sec) in the unmasked conditions of the current study (black bars) and the previous study (red bars). Error bars indicate one standard error above the mean.

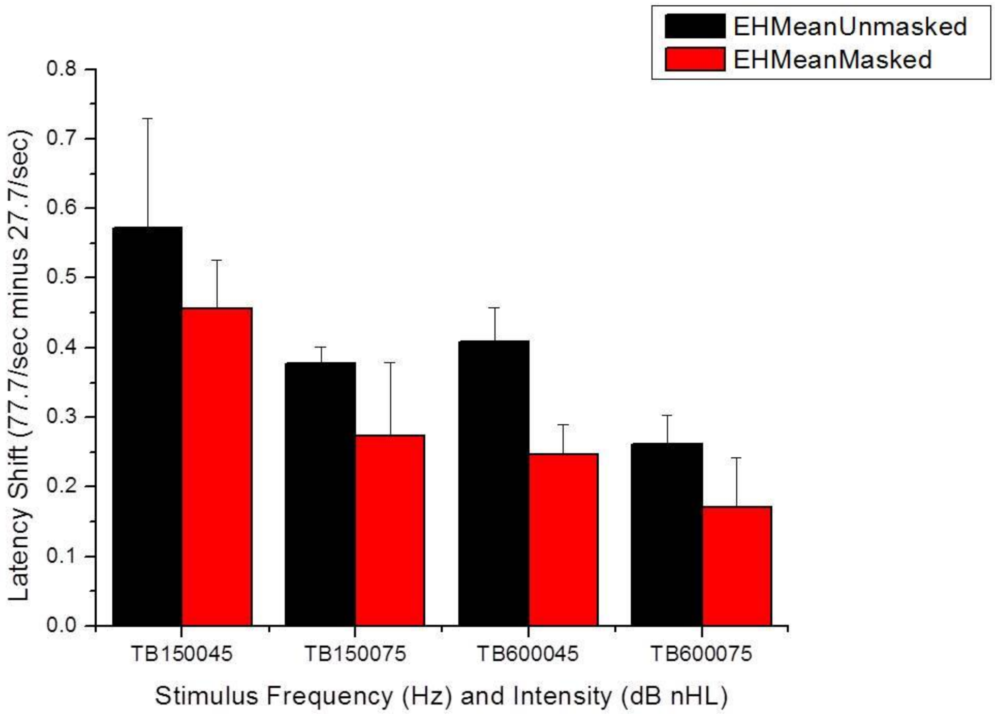

Figure 4. Mean rate-induced Wave V latency shift observed (with an increase in stimulus rate from 27.7/sec to 77.7/sec) in the unmasked (black bars) and masked (red bars) conditions of the current study. Error bars indicate one standard error above the mean.

Chapter 4: Discussion and Conclusions

Effects of High-Pass Masking

The primary goal of the current study was to apply high-pass masking to the previous paradigm to determine if previous findings were appropriately isolated to low and high frequency regions. ABR Wave V latency was measured in normal hearing adults in sixteen stimulus conditions, varying in stimulus frequency (1500 and 6000 Hz), intensity (45 and 75 dB nHL), rate (27.7 and 77.7 per second), and presence or absence of high-pass masking noise. Addition of high-pass masking resulted in an increase in mean absolute Wave V latency almost universally. The magnitude of this increase in Wave V latency with masking varied with frequency and intensity. The greatest effect was observed in the low frequency conditions, particularly the low frequency, low intensity condition. These results are consistent with previous research demonstrating increased Wave V latency in the presence of high-pass masking noise (Oates & Stapells, 1997). Oates and Stapells (1997) recorded unmasked and masked ABR responses to 500 and 2000 Hz tonebursts and results revealed a universal increase in Wave V latency with addition of high-pass masking noise, with greater increases in latency observed in the low frequency (500 Hz) conditions compared to the high frequency (2000 Hz) conditions. This greater increase in latency for low frequency conditions was hypothesized to reflect longer cochlear delays associated with activation of the apical portion of the cochlea (Oates & Stapells, 1997). Although stimulus frequencies employed by Oates & Stapells were distinct from those used in the current study, similar results were observed in both studies. Mean absolute Wave V latency increased in the presence of high-pass masking and this effect varied with stimulus frequency. The observed increase in Wave V latency with masking was greater for low frequency conditions than high frequency conditions and this finding was consistent across both studies. Oates & Stapells (1997) did not examine stimulus intensity as a variable and all stimuli were presented at 52-53 dB nHL; therefore, no comparisons can be drawn between intensity effects in the current and previous study. In addition, Oates & Stapells (1997) presented all stimuli at a rate of 9.4 per second, thus eliminating stimulus rate as a variable.

A greater increase in absolute Wave V latency with addition of high-pass masking may be more likely in low frequency stimulus conditions compared to high frequency stimulus conditions for several reasons. First, higher frequency regions of the cochlea display better neural synchrony of responses to stimulation. Therefore, poorer neural synchrony of the lower frequency regions of the cochlea may result in a more pronounced effect of high-pass masking on ABR responses (Kiang, 1975). In addition, there is a longer cochlear delay associated with apical cochlear activation compared to basal activation (Bekesy, 1960). Thus, the longer cochlear delay times in response to low frequency stimuli may be more likely to display even greater delay with the addition of masking noise compared to the shorter cochlear delay times observed in response to high frequency stimuli.

Upon examination of the effect of high-pass masking on rate-induced Wave V latency shift, it is clear that addition of masking noise resulted in decreased rate-induced Wave V latency shift across all conditions in the current study. This effect was greatest in the high frequency, low intensity stimulus condition. Despite slight differences in the degree of rate-induced Wave V latency shift reduction between unmasked and masked conditions, the general relationship between each unmasked condition and the corresponding masking condition remained similar. These results are supported by previous research examining rate and masking noise effects on ABR Wave V latency (Burkard & Hecox, 1983). Burkard & Hecox (1983) specifically examined effects and interactions of varied stimulus rates and levels of masking noise on Wave V latency. Although click stimuli were utilized rather than frequency-specific stimuli, the results demonstrated decreased magnitude of rate-induced Wave V latency shift with addition of masking noise. Specifically, the rate-induced Wave V latency shift continued to decrease in magnitude with increasing level of masking noise. Burkard & Hecox examined these masking effects using broadband masking noise, differing from the high-pass masking noise utilized in the current study. Despite these differences, the findings of the previous study are consistent with the present study and confirm the observed decrease in rate-induced Wave V latency shift in the presence of masking noise (Burkard & Hecox, 1983). This interaction between rate effects and high-pass masking effects suggests a difference in the pattern of cochlear activation in response to lower rate stimuli compared to higher rate stimuli. The reduction in rate-induced Wave V latency shift observed in the presence of masking noise may suggest more basal spread of activation in response to lower rate stimuli than higher rate stimuli. Greater off-frequency activation for lower rate stimuli would result in a greater effect of masking on the lower rate stimuli than the higher rate. The resulting greater Wave V latency shift for masked lower rate stimuli, in combination with the lesser Wave V latency shift for masked higher rate stimuli, would explain the smaller rate-induced Wave V latency shift for masked conditions compared to unmasked conditions. The exact mechanisms behind this finding remain unclear, and further research on this effect of high-pass masking noise on rate-induced Wave V latency shift is warranted.

Comparison of Wave V Latency and Shift

A secondary goal of this study was to replicate findings of the previous study (Hess & Hood, 2012). Results obtained in the unmasked conditions of the current study and those measured in the previous study were expected to reveal comparable measurements of mean absolute Wave V latency and mean rate-induced Wave V latency shift. Qualitatively comparable results were obtained in the previous and current studies and the mean values are displayed in Figure 3, which compares mean rate-induced Wave V latency shift measured in the previous study and unmasked conditions of the current study.

In conclusion, patterns observed in the previous study were confirmed in the present study and measured effects were preserved with the addition of high-pass masking noise, verifying the frequency specificity of the stimuli. The significantly greater rate-induced Wave V latency shift in the low frequency, low intensity condition was consistent between studies and remained in the presence of masking. Results of the current study suggest that the observed rate-induced Wave V latency shift is a frequency- and intensity-specific effect, due to the absence of a latency shift of similar magnitude in the low frequency, high intensity condition.

Based on the frequency- and intensity-specific nature of this effect, it is hypothesized that the difference in rate-induced Wave V latency shift for the low frequency, low intensity stimulus condition may be related to differential firing patterns of low- and high-spontaneous rate auditory nerve fibers. Auditory nerve fibers deliver signals from inner hair cells of the cochlea to the cochlear nucleus. Each individual auditory nerve fiber receives signals from one inner hair cell; however, 10-30 auditory nerve fibers innervate each inner hair cell, depending on cochlear site and species (Bohne, Kenworthy, & Carr, 1982; Liberman, Dodds, & Pierce, 1990; Stamanski, Francis, Lehar, May, & Ryugo, 2006). This pattern of innervation is vital in auditory processing, because the multiple auditory nerve fibers which innervate a single inner hair cell vary in spontaneous discharge rate and acoustic stimulation threshold. Research demonstrates that low spontaneous rate fibers display higher stimulation thresholds, while high spontaneous rate fibers exhibit lower stimulation thresholds (Liberman, 1978). This range of auditory nerve fibers with differing stimulation thresholds allows for increased dynamic range of the auditory periphery. In addition, the low-spontaneous rate, high-threshold fibers are crucial for hearing in loud environments, based on their resistance to masking by continuous background noise (Costalupes, Young, & Gibson, 1984).

Therefore, in the current study, ABR waveforms recorded in response to low intensity stimuli may be thought of as a product of high-spontaneous rate, low-threshold auditory nerve fibers. However, those responses recorded in high intensity stimulus conditions may be the result of both high-spontaneous rate, low-threshold fibers and low-spontaneous rate, high-threshold fibers. This difference in the population of auditory nerve fibers firing in response to high and low intensity stimuli could contribute to the greater rate-induced Wave V latency shift observed for the low frequency, low intensity condition in the current study. Since only the lower-threshold auditory nerve fibers are expected to fire in response to a lower intensity stimulus, those responses may be more vulnerable to the effects of increased stimulus rate.

Study Limitations

The current study was not an exhaustive examination of stimulus parameters across the ranges of frequency, intensity, and rate. Investigating only two variations of each stimulus parameter does not provide a comprehensive representation of the effects across a wider range of parametric changes. The current study gives additional insight regarding effects and interactions of stimulus frequency, intensity, rate, and masking; however, further parametric studies are necessary to gain more complete details.

Additionally, the present study is limited to young adults with normal hearing. This population was selected for the current study in order to allow for direct comparison with the previous study, as well as to provide a baseline dataset across the stimulus parameters examined. This baseline dataset will serve as a reference for further studies, including continuation of data acquisition in infants and older adults with normal peripheral hearing.

Future Research

The current study provided details regarding the effects and interactions of stimulus frequency, intensity, rate, and masking on Wave V latency of the ABR in normal hearing young adults. The next step is to examine these effects in greater detail, particularly frequency and intensity effects. Future research will involve recording ABR responses at additional frequencies across a broader range to gain a more comprehensive profile of frequency effects. Future studies may include creation of an extensive input-output intensity function to provide additional details on the effects of intensity. Such investigations would be time-intensive, as the increased number of stimulus parameters would require lengthy testing sessions.

Results of the current study have possible implications in pediatric ABR threshold determination, particularly in regards to using faster stimulus rates in pediatric testing. Based on the results found in the normal hearing young adult population, if faster stimulus rates are used with lower frequency tonebursts and at lower intensities in the process of determining response thresholds, longer latencies than previously expected may be measured in the infant population. Previous studies demonstrate a significant effect of stimulus rate on ABR Wave V latency in the infant population; however, most of these studies have used click stimuli at high intensities (Parthasarathy, Borgsmiller, & Cohlan, 1998). Since toneburst ABR testing for threshold estimation is now the standard of care, further research in the infant population is necessary to define the effect of stimulus rate on Wave V latency, as well as interaction of rate effects with frequency and intensity effects (AAA, 2012).

Additionally, this research could be expanded to include the older adult population. Age-related hearing loss, or presbycusis, can result in both increased hearing thresholds and changes in temporal processing, denoting both possible peripheral and central pathology (Boettcher, White, Mills, & Schmeidt, 1995; Gordon-Salant & Fitzgibbons, 1993). Studies of ABR characteristics in older adults have shown variable results, which may be related to the specific stimuli and recording parameters used in these studies (Walton, Orlando, & Burkard, 1999; Burkard & Sims, 2001; Konrad-Martin et al., 2012). Examining the effects and interactions of the stimulus parameters employed in the current study in the older adult population may provide further insight into the aging auditory system.

Conclusion

The primary purpose of this study was to apply high-pass masking to the previous paradigm to determine if previous findings were isolated to low and high frequency regions. Patterns observed in the previous study were confirmed in the present study and measured effects were preserved with the addition of high-pass masking noise, verifying the frequency specificity of the stimuli. The secondary purpose was to replicate the findings of the previous study. The significantly greater rate-induced Wave V latency shift in the low frequency, low intensity condition was consistent between studies and remained in the presence of masking. Results of the current study suggest that the measured rate-induced Wave V latency shift is a frequency- and intensity-specific effect, due to the absence of a latency shift of similar magnitude in the low frequency, high intensity condition. The difference in the population of auditory nerve fibers firing in response to high and low intensity stimuli could contribute to the greater rate-induced Wave V latency shift observed for the low frequency, low intensity condition. Given the limited frequency and intensity parameters employed in the current study, as well as the normal hearing young adult population examined, further research is warranted.

References

American Academy of Audiology. (2012). Audiologic guidelines for the assessment of hearing in infants and young children. Retrieved from http://www.audiology.org/resources/documentlibrary/Documents/201208_AudGuideAssessHear_youth.pdf.

Beattie, R.C. (1988). Interaction of click polarity, stimulus level, and repetition rate on the auditory brainstem response. *Scandinavian Audiology, 17*, 99-109.

Beattie, R.C., & Rochverger, I. (2001). Normative behavioral thresholds for short tone-bursts. *Journal of the American Academy of Audiology, 12*, 453-461.

Bekesy, G. von (1960). *Experiments in Hearing.* New York: McGraw-Hill.

Boettcher, F.A., White, D.R., Mills, J.H., & Schmeidt, B.N. (1995). Age-related changes in auditory evoked potentials of gerbils. III. Low-frequency responses and repetition rate effects. *Hearing Research, 87,* 208-219.

Bohne, B.A., Kenworthy, A., & Carr, C.D. (1982). Density of myelinated nerve fibers in the chinchilla cochlea. *Journal of the Acoustical Society of America, 72,* 102-107.

Burkard, R., & Hecox, K. (1983). The effect of broadband noise on the human brainstem auditory evoked response. I. Rate and intensity effects. *Journal of the Acoustical Society of America, 74*(4), 1204-1213.

Burkard, R.F., & Sims, D. (2001). The human auditory brainstem response to high click rates: Aging effects. *American Journal of Audiology, 10,* 53-61.

Costalupes, J.A., Young, E.D., & Gibson, D.J. (1984). Effects of continuous noise backgrounds on rate response of auditory nerve fibers in cat. *Journal of Neurophysiology, 51*, 1326-1344.

Davis, H., & Hirsch, S.K. (1976). The audiometric utility of brain stem responses to low-frequency sounds. *Audiology, 15*, 181-195.

Don, M., Allen, A.R., & Starr, A. (1977). Effect of click rate on the latency of auditory brainstem responses in humans. *Annals of Otololgy, Rhinology, and Laryngology, 86,* 186-195.

Don, M., & Eggermont, J.J. (1978). Analysis of the click-evoked brainstem potentials in man using high-pass masking. *Journal of the Acoustical Society of America, 63,* 1084-1092.

Eggermont, J.J., & Don, M. (1980). Analysis of the click-evoked brainstem potentials in humans using high-pass noise masking. II. Effect of click intensity. *Journal of the Acoustical Society of America, 68,* 1671-1675.

Fowler, C.G., & Noffsinger, D. (1983). Effects of stimulus repetition rate and frequency on the auditory brainstem response in normal, cochlear-impaired, and VIII nerve/brainstem-impaired subjects. *Journal of Speech, Language, and Hearing Research, 26,* 560-567.

Gordon-Salant, S., & Fitzgibbons, P.J. (1993). Temporal factors and speech recognition performance in young and elderly listeners. *Journal of Speech, Language, and Hearing Research*, *36*, 1276-1285.

Gorga, M. P., Kaminski, J. R., Beauchaine, K. A., & Jesteadt, W. (1988). Auditory brainstem responses to tone bursts in normally hearing subjects. *Journal of Speech and Hearing Research, 31*, 87–97.

Hess, B. & Hood, L.J. (2012). Effect of stimulus type, rate, and intensity on the ABR. Annual Scientific and Technology Meeting of the American Auditory Society, Scottsdale, Arizona.

Kavanagh, K.T., Harker, L.A., & Tyler, R.S. (1984). Auditory brainstem and middle latency responses. I. Effects of response filtering and waveform identification. *The Annals of Otology, Rhinology & Laryngology*, *93*(Sup 108):1-12.

Kiang, N.Y.S. (1975). Stimulus representation in the discharge patterns of auditory neurons. In D.B. Tower (Ed.), *The Nervous System, Vol. 3: Human Communication and Its Disorders* (81-96). Raven, New York: Raven Press Publishers.

Klein, A.J. (1986). Masking effects on ABR waves I and V in infants and adults. *Journal of the Acoustical Society of America*, *79*(3), 755-759.

Konrad-Martin, D., Dille, M.F., McMillan, G., Griest, S., McDermott, D., Fausti, S.A., & Austin, D.F. (2012). Age-related changes in the auditory brainstem response. *Journal of the American Academy of Audiology, 23,* 18-35.

Laukli, E. (1983a). Stimulus waveforms used in brainstem response audiometry. *Scandinavian Audiology, 12*, 83-89.

Laukli, E. (1983b). High-pass and notch noise masking in suprathreshold brainstem response audiometry. *Scandinavian Audiology, 12*, 109-115.

Liberman, M.C. (1978). Auditory-nerve response from cats raised in a low-noise chamber. *Journal of the Acoustical Society of America, 63*, 442-455.

Liberman, M.C., Dodds, L.W., & Pierce, S. (1990). Afferent and efferent innervation of the cat cochlea: quantitative analysis with light and electron microscopy. *Journal of Comparative Neurology, 301,* 443-460.

Mackersie, C., Down, K.E., & Stapells, D.R. (1993). Pure-tone masking profiles for human auditory brainstem and middle latency responses. *Hearing Research, 65*, 61-68.

Newton, E.H., Cooper, W.A., & Coleman, J.R. (1992). Rate and frequency interactions in the auditory brainstem response of the adult rat. *Hearing Research, 60,* 73-79.

Nousak, J.M.K., & Stapells, D.R. (1992). Frequency specificity of the auditory brain stem response to bone-conducted tones in infants and adults. *Ear and Hearing, 13*, 87-95.

Oates, P., & Stapells, D.R. (1997). Frequency specificity of the human auditory brainstem and middle latency responses to brief tones. I. High-pass noise masking. *Journal of the Acoustical Society of America, 102*(6), 3597-3608.

Oxenham, A.J., & and Simonson, A.M. (2009). Masking release for low- and high-pass-filtered speech in the presence of noise and single-talker interference. *Journal of the Acoustical Society of America, 125*(1): 457–468.

Parthasarathy, T.K., Borgsmiller, P., & Cohlan, B. (1998). Effects of repetition rate, phase, and frequency on the auditory brainstem response in neonates and adults. *Journal of the American Academy of Audiology, 9*, 134-140.

Picton, T.W., Ouelette, J., Hamel, G., & Smith, A.D. (1979). Brainstem evoked potentials to tonepips in notched noise. *American Journal of Otolaryngology, 8*, 289-314.

Spoendlin, H. (1972). Innervation densities of the cochlea. *Acta Otolaryngologica, 73,* 235-248.

Stamanski, S., Francis, H.W., Lehar, M., May, B.J., & Ryugo, D.K. (2006). Synaptic alterations at inner hair cells precede spiral ganglion cell loss in aging C57BL/6J mice. *Hearing Research, 221*, 104-118.

Stapells, D.R., & Oates, P. (1997). Estimation of the pure-tone audiogram by the auditory brainstem response: A review. *Audiology and Neurotology, 2*, 257-280.

Stapells, D.R., & Picton, T.W. (1981). Technical aspects of brainstem evoked potential audiometry using tones. *Ear and Hearing, 2*, 20-29.

Stapells, D.R., Picton, T.W., & Durieux-Smith, A. (1994). Electrophysiologic measures of frequency-specific auditory function. In J.T. Jacobson (Ed.), *Principles and Applications in Auditory Evoked Potentials* (251-283). Boston: Allyn and Bacon.

Walton, J., Orlando, M., & Burkard, R. (1999). Auditory brainstem response forward-masking recovery functions in older humans with normal hearing. *Hearing Research, 127*, 86-94.

Weber, B.A., & Fujikawa, S.M. (1977). Brainstem evoked response (BER) audiometry at various stimulus presentation rates. *Journal of the American Audiology Society, 3*, 59-62.