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The relation between speech recognition in noise and the speech-evoked brainstem response in normal-hearing and hearing-impaired individuals

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THE RELATION BETWEEN SPEECH RECOGNITION IN NOISE AND THE SPEECH-EVOKED BRAINSTEM RESPONSE IN NORMAL-HEARING AND HEARING-IMPAIRED INDIVIDUALS

by

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Abstract:* *Little is known about the way speech in noise is processed along the auditory pathway. The purpose of this study was to evaluate the relation between listening in noise using the R-Space system and the neurophysiologic response of the speech-evoked auditory brainstem when recorded in quiet and noise in adult participants with mild to moderate hearing loss and normal hearing.

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ABBREVIATIONS

ABR	Auditory Brainstem Response
AEP	Auditory Evoked Potential
CNC	Consonant/Nucleus/Consonant Test
Cz	Vertex
dB	Decibel
df	Degrees of Freedom
F_0	Fundamental Frequency
FFT	Fast Fourier Transform
HINT	Hearing in Noise Test
HL	Hearing Loss
Hz	Hertz
NH	Normal Hearing
PTA	Pure Tone Average
RMS	Root Mean Square
RTS	Reception Threshold for Speech
SD	Standard Deviation
SEABR	Speech-evoked Auditory Brainstem Response
SIN	Speech in Noise
SNR	Speech to Noise Ratio
SPL	Sound Pressure Level

INTRODUCTION

The ability to understand speech in the presence of background noise is an intricate task. Whether carrying on a conversation while walking down a traffic-filled street or sitting within a busy restaurant, our daily dialogue is embedded in high levels of noise and it is the job the brain to extract the important signals and messages. The beginning stages of this process happen subcortically with the help of the neural synchrony of the brainstem (Pressnitzer et al., 2008). Technology has provided the tools to measure this neural synchrony within the brainstem by eliciting and recording auditory evoked potentials.

Auditory evoked potentials are electrophysiologic responses within the auditory system that are produced by sounds. The auditory brainstem response (ABR) has traditionally been elicited using a click or tone burst stimulus. It is utilized clinically to provide objective information about hearing sensitivity at the individual level. Recent studies have shown that the ABR can also be extracted using a speech stimulus (Cunningham et al., 2001; Johnson et al., 2005; Song et al., 2006; Akhoun et al., 2008).

The Speech-evoked Auditory Brainstem Response (SEABR) is a measure that maintains intrasubject reliability across test sessions (Song, Nicol, and Kraus, 2010) and has been used to objectively evaluate speech encoding at the level of the brainstem. The speech stimulus that is often used to elicit the waveforms is a /da/ stimulus; it encompasses an initial tone burst of the consonant, which transitions into the steady-state vowel. The brainstem's electrophysiologic response to this stimulus is a complex waveform, which includes transient and sustained elements (Russo et al.., 2004). The speech stimulus produces a neural response with seven discrete peaks: V, A, C, D, E, F and O. Waves V and A make up the onset response complex, waves C through F are response peaks that represent the consonant to vowel transition as well as the periodicity of the stimulus and finally wave O reflects the offset of the stimulus (Kraus & Nicol, 2005; Johnson, Nicol & Kraus, 2005). Similar to the ABR, measures of latency and amplitude can be used to examine the SEABR. Latency reflects the timing needed to accurately encode the stimulus and amplitude reflects the magnitude of the response.

It has been well documented using objective measures that the neural synchrony of the SEABR is robust when the signal is presented in quiet, however degrading occurs in the presence of background noise; latencies are delayed and amplitudes reduced among the wave components (Johnson, Nicol & Kraus, 2005; Russo et al., 2004). Subjectively, patients report this same theme, where the ability to understand speech in the presence of background noise is a laborious task as compared to listening in quiet. It takes increased focus and effort to understand someone who is among a noisy crowd as compared to speaking to that person in a one-on one setting. Consonants, the parts of speech that carry meaning, are difficult to perceive in noisy situations because they are rapid, relatively low-amplitude transient features of speech. In particular, stop consonants, such as /d/, are known to be vulnerable to disruption by background noise (Russo et al., 2004; Cunningham, 2002).

Individuals with hearing loss have greater difficulty in noisy situations than normal hearing counterparts; even individuals with only a mild hearing loss experience increased listening effort in the presence of noise (Dubno, 1984). In addition, individuals with hearing loss also have reduced release from masking (Eisenberg, 1995; Best, 2011); in other words these individuals have a harder time moving and adjusting between noisy and quiet environments.

Although individuals with hearing loss typically sustain greater difficulty when listening in noise than individuals with normal hearing, all individuals, including those with normal hearing sensitivity have trouble listening when competing auditory signals exist. It is difficult to predict how a person will perform in noisy or reverberant listening situations from their audiogram alone; this maybe due to the fact that hearing thresholds are obtained in an quiet sound-treated booth. The efficiency with which the auditory system encodes sounds can also differ across listeners and there are many debated reasons as to why the spectrum exists. A study done by Ruggles, et al. (2011) found significant intersubject differences in how well normal hearing individuals were able to focus on one key signal when many signals were presented simultaneously.

Research supports the relationship between neural deficits due to noise and behavioral speech-in-noise (SIN) perception. Anderson, et al. (2010a), investigated whether children with documented poor SIN perception had greater noise-induced neural response delays than children with good SIN perception. The children were evaluated using the Hearing in Noise Test (HINT), which alters the intensity of the target sentence relative to the constant speech-shaped noise masker in order to achieve a signal-to-noise ratio (SNR) threshold. Based on HINT performance the children were divided into top and bottom SIN groups. They were then evaluated using the SEABR Neuroscan System with the /da/ stimulus present in both quiet and in multi-talker noise. Results showed that, in quiet, both groups of children had equivalent neural response latencies. However in noise, while all children had significantly delayed brainstem responses as compared to the quiet condition, the children with poor SIN perception had increased delays in latency and formant transition.

Anderson and colleagues (2010b) subsequently examined the brainstem encoding of pitch in 38 typically developing school-age children who had an array of SIN perception abilities. Their speech understanding in noise performance was evaluated using HINT sentences. The full HINT protocol consists of three conditions: HINT-Front, HINT-Right and HINT-Left, however they chose to only use the HINT-Front subtest in order to remove the effects of spacial cues requiring the children to rely only on acoustic cues such as pitch. Anderson and colleagues were particularly interested in the subcortical encoding of pitch, which is determined by low harmonics, because pitch has been previously identified as and essential factor in SIN perception. Results showed that there were significant differences in low-frequency spectral encoding, in the formant transition region, between the two test groups. The children who had poor SIN perception were found to have decreased spectral magnitudes for the fundamental frequency (F_0), which are important cues for pitch perception. These results suggest that the robustness of the neural encoding of pitch may be a key aspect in the success of speech recognition in noise.

In 2011, Anderson et al.. investigated the neural basis of speech recognition in noise in adults over 60 years of age. Participants speech in noise performance was again evaluated using the adaptive HINT. Individual scores were used to form two groups of top and bottom performers. The participant's speech-evoked ABR recordings were also compared. Results showed that the bottom group had decreased magnitudes for the F_0 and lower RMS amplitudes as compared to the top group. In addition, the quiet-to-noise response correlations showed that the bottom group had a greater dissimilarity between their responses in quiet and responses in noise as compared to the top group. These results suggest the importance of F_0 encoding for successful SIN performance.

In 2011, Song, et al. investigated the relation between SIN perception and the neural representation of the F_0 in the brainstem, using the SEABR, in young adults between 20 and 30 years of age. Participants were evaluated for SIN using the Quick Speech-in-Noise Test in four-talker babble and were subsequently divided into two groups based on their median SIN score.

Results showed that while background noise weakened the F_0 amplitudes in top and bottom performers, bottom performers were more greatly affected.

As seen in the majority of the aforementioned research studies, the adaptive HINT is a useful test to determine speech-in-noise performance; however it is important that the task replicate real-life as much as possible to more meaningfully assess everyday listening. Often, patients report that listening in a static sound booth is much easier compared to listening in the environment. Testing in a laboratory setting can be contrived and therefore may not reflect the difficulty a listener has during communication situations.

The R-Space system uses background of noise that was recorded in a busy restaurant and HINT sentences to evaluate SIN performance. It is a system that was designed to reflect a life-like listening environment for the individual who is seated at the center of the eight-loudspeaker 360-degree array (Revit et al., 2002; Compton-Conley et al., 2004). The participant is asked to repeat the sentences presented from the front (0 degree) loudspeaker, while the restaurant noise is heard from all surrounding loudspeakers. The noise remains at a constant level, while the level of the sentences is adjusted based on the correctness of the response, altering the signal-to-noise ratio.

The objective of the current study was to evaluate the relation between listening in noise using the R-Space as described and the neurophysiologic response of the speech-evoked auditory brainstem when recorded in quiet and noise in individuals with mild hearing loss and normal hearing.

METHODS

Participants

The study protocol was approved by the Human Research Protection Office at Washington University School of Medicine (#09-1751). Hearing-impaired individuals were recruited from the Washington University in St. Louis School of Medicine Division of Adult Audiology and Volunteer for Health services. Individuals with normal hearing were recruited from the Washington University community and Volunteer for Health services. All participants were at least 18 years of age and informed consent was obtained from each individual prior to beginning the study. Participants were reimbursed for their time and travel.

Hearing Impaired (HI) Participants

Nine adults with a mild to moderate sensorineural hearing loss (eight females and one male, ages 44-71, (mean 58.6, SD 8.12) participated in the study. A mild to moderate hearing loss was characterized as thresholds ≤ 50 dB HL from 250 Hz to 4 kHz. Auditory thresholds were obtained using the Hughson-Westlake procedure (Carhart & Jerger, 1959). The mean pure-tone average (PTA = mean of audiometric thresholds at 500, 1000 and 2000 Hz) was 29 dB HL for the right ear and 29 dB HL for the left ear. Average audiometric thresholds for the HL participants are shown in Figure 1. The average age that the hearing loss participants reported first noticing their hearing loss was 49.78 years and the average age of diagnosis was 51.67 years.

Normal Hearing (NH) Participants

Nine adults (eight females and one male, ages 46-74, mean 59.8, SD 8.7) served as normal hearing controls. NH participants were matched based on age (± 5 years) and gender to an individual in the hearing loss group. NH adults had pure-tone audiometric thresholds equal to or better than 25 dB HL in both ears from 250 Hz to 4 kHz. The mean PTA was 10 dB HL for the right ear and 9 dB HL for the left ear. Average audiometric thresholds for the NH participants are shown in Figure 2.

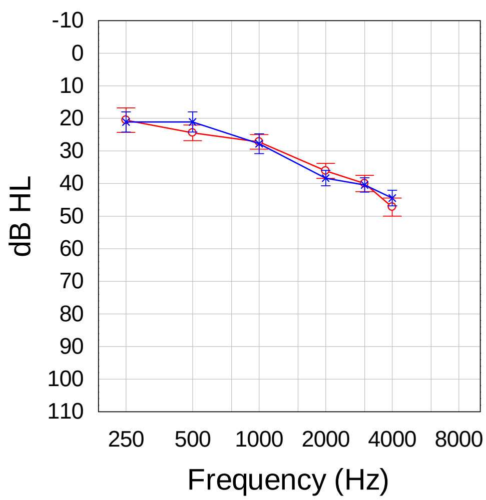

Figure 1: *Mean thresholds from 250 Hz to 4,000 Hz for HL participants including standard error*

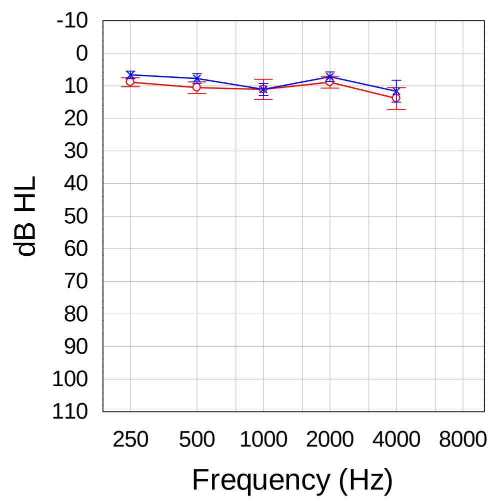

Figure 2: *Mean thresholds from 250 Hz to 4,000 Hz for NH participants including standard error*

Experimental Design

Speech-evoked ABRs were recorded under the following conditions: 80 dB SPL in quiet (right ear (RE only), 80 dB SPL with +10 SNR pink noise (RE only), 80 dB SPL in quiet (bilateral), and 80 dB SPL with +10 SNR pink noise (bilateral). Conditions were randomized for each participant at each test session and two test sessions were completed to obtain test-retest measures. Two trials of 3000 sweeps were collected for each listening condition. These two trials were averaged to create a calculated wave of 6000 sweeps. SEABR waveform peaks were identified by the primary researcher and were confirmed by the capstone advisor. If a peak could not be clearly identified it was not marked.

R-Space testing was recorded under the following conditions, 70 dB SPL RE only and 70 dB SPL binaural testing. During the RE only condition, the participants left ear was plugged and muffed in order to eliminate audibility in the non-test ear. Two randomized HINT sentence lists were selected for each condition at each test session. Two test sessions were completed to obtain test-retest measures.

Testing equipment/Setup

All testing was performed at the Washington University School of Medicine Department of Otolaryngology. Hearing thresholds and R-Space testing were performed in a double-walled sound-treated booth and SEABR testing was performed in a single-wall sound-treated booth.

A Grason-Stadler GSI-61 audiometer was used for determining hearing thresholds with THD-49 circumaural headphones.

SEABR testing was completed using the Bio-logic Auditory Evoked Potential (AEP) System v7 with BioMARK™ software v2 was used with the Bio-logic Navigator Pro unit to collect and analyze all waveforms. Reusable metal disc electrodes were placed on the vertex of the head (Cz) and the backside of each earlobe. Bio-logic ER3A insert earphones with foam tips were used to present the stimuli. During testing, the examiner was seated outside the booth with the recording equipment. Participants were seated in a comfortable chair with a headrest. Each chose one of three activities, either watch a closed-captioned movie, read a book or rest. Participants were instructed to relax and refrain from moving.

R-Space was performed with the participant seated at the center of an eight loudspeaker circular array. Each loudspeaker was 44 inches above the ground, approximately at ear level for a seated adult, and at a distance of 24 inches from the participant. The loudspeakers were equally spaced in increments of 45º around the participant. See Figure 3 for a schematic illustration of the R-Space loudspeaker system. The equipment used to operate the R-Space system included an Apple IMAC 17 personal computer with a 2 GHz Intel Core 2 Duo Processor, 2 GB of memory, and MAC OS 10 operating system. In addition, the R-Space configuration was executed via professional audio mixing software (MOTU Digital Performer 5) and an audio interface (MOTU 828mkII, 96 kHz firewire interface). The output of the audio interface was sent to four amplifiers (ART SLA-1, two-channel stereo linear power amp with 100 watts per channel) and then to the eight loudspeakers (Boston Acoustic CR67). A Dell personal computer with a 24-bit studio sound card, a power amplifier, and an Urei 809A time align studio monitor loudspeaker was utilized to present CNC words in the soundfield.

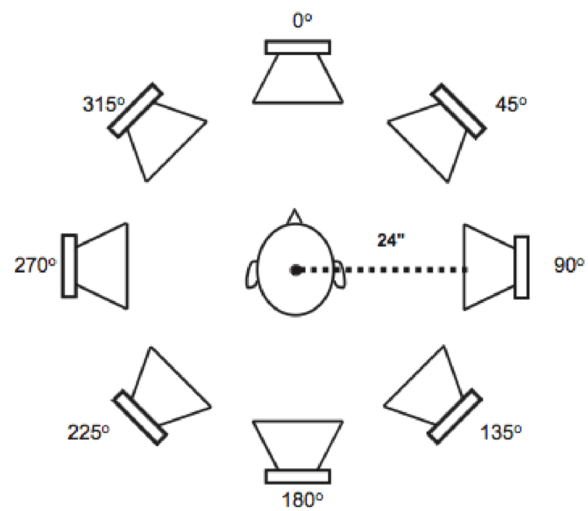

Figure 3*: Schematic illustration of the R-Space system loudspeaker arrangement. Figure taken from Compton-Conley et al. (2004).*

The Brainstem Toolbox (MATLAB vR2009B) was used to calculate spectral encoding and overall root mean square (RMS) amplitudes between the NH and HL groups for the SEABR. The sustained spectral portion of the response (the area between Wave C and O) was analyzed with Fast Fourier Transform (FFT). This analysis included three frequency regions: 103- 121 Hz (F0, fundamental frequency), 454-719 Hz (F, first formant) and 721-1155 Hz (F2, second formant) and provided information on the precision and magnitude of phase- locking in these frequency regions. Modifications to the Toolbox were completed to account for timing differences between the quiet and noise conditions.

Recording Parameters

Three electrodes were used to obtain a single-channel recording: (vertex (Cz) active, right earlobe reference, left earlobe ground. Impedance values were checked and optimized at the beginning of each session at a level 5 kΩ or better, and all three electrodes were within 3 kΩ of one another. Generation of the waveform included an epoch time of 85.33 ms (pre-stimulus 17.4 ms, post-stimulus 67.93 ms) and 1024 data points. Gain was set to 100,000 with artifact rejection occurred when responses were larger than +/- 23.8 μV. Filters were set at 100 Hz and 2000 Hz.

RESULTS

The statistical analysis conducted was a 2 (listening condition: quiet/noise) x 2 (hearing status: NH/HL) x speech recognition (R-Space) repeated measures multiple regressions with the first factor treated as a repeated measure, the second factor treated as a between-subjects variable and the last factor treated as a continuous variable. All main effects and interactions are tested.

Speech-evoked ABR

Individual waveforms

Mean latency based on each participant's individually marked waves and the corresponding standard deviations are shown in Table 1. Mean amplitude based on each participant's individually marked waves and the corresponding standard deviations are shown in Table 2.

	V Lat. (SD)	A Lat. (SD)	C Lat. (SD)	D Lat. (SD)	E Lat. (SD)	F Lat. (SD)	O Lat. (SD)
NH RE Quiet	6.80 (0.47)	7.93 (0.79)	18.44 (0.53)	22.94 (1.08)	31.54 (0.71)	39.92 (0.91)	48.75 (0.87)
NH RE Noise	7.02 (0.64)	8.38 (0.81)	19.16 (0.69)	23.77 (1.33)	32.13 (0.81)	40.11 (1.02)	49.71 (1.31)
NH Bilat Quiet	6.85 (0.43)	8.10 (0.79)	18.77 (0.45)	23.37 (0.86)	32.07 (0.70)	40.04 (0.78)	49.00 (0.75)
NH Bilat Noise	7.23 (0.57)	8.43 (0.57)	19.58 (0.63)	24.24 (0.91)	32.20 (0.91)	40.23 (1.06)	49.61 (1.27)
HL RE Quiet	6.96 (0.38)	8.08 (0.54)	18.94 (0.75)	23.10 (0.71)	31.81 (1.06)	39.93 (0.48)	50.09 (1.19)
HL RE Noise	7.12 (0.74)	8.48 (0.80)	19.26 (0.89)	23.28 (1.03)	31.86 (1.27)	40.11 (0.63)	50.35 (1.14)
HL Bilat Quiet	6.88 (0.40)	8.08 (0.53)	19.12 (0.66)	23.17 (0.76)	31.83 (0.75)	39.95 (0.41)	50.38 (1.12)
HL Bilat Noise	7.10 (0.49)	8.47 (0.69)	19.49 (0.83)	23.58 (0.96)	31.75 (0.73)	39.97 (0.45)	50.62 (1.27)

Table 1: *Mean SEABR latencies (ms) with SD for quiet and noise in each group*

	V Amp. (SD)	A Amp. (SD)	C Amp. (SD)	D Amp. (SD)	E Amp. (SD)	F Amp. (SD)	O Amp. (SD)
NH RE Quiet	0.09 (0.06)	-0.15 (0.06)	-0.03 (0.04)	-0.12 (0.07)	-0.17 (0.08)	-0.15 (0.06)	-0.14 (0.06)
NH RE Noise	0.04 (0.05)	-0.06 (0.06)	-0.02 (0.03)	-0.04 (0.03)	-0.09 (0.07)	-0.11 (0.07)	-0.08 (0.03)
NH Bilat Quiet	0.17 (0.07)	-0.23 (0.09)	-0.02 (0.06)	-0.20 (0.10)	-0.25 (0.09)	-0.19 (0.14)	-0.21 (0.10)
NH Bilat Noise	0.08 (0.06)	-0.10 (0.10)	-0.02 (0.04)	-0.07 (0.06)	-0.14 (0.10)	-0.19 (0.10)	-0.11 (0.06)
HL RE Quiet	0.05 (0.04)	-0.14 (0.05)	-0.06 (0.05)	-0.12 (0.08)	-0.19 (0.08)	-0.09 (0.06)	-0.09 (0.05)
HL RE Noise	0.04 (0.03)	-0.08 (0.06)	-0.03 (0.05)	-0.05 (0.06)	-0.11 (0.06)	-0.12 (0.07)	-0.09 (0.06)
HL Bilat Quiet	0.12 (0.07)	-0.22 (0.08)	-0.06 (0.05)	-0.20 (0.11)	-0.31 (0.11)	-0.20 (0.15)	-0.14 (0.08)
HL Bilat Noise	0.07 (0.05)	-0.16 (0.07)	-0.02 (0.03)	-0.11 (0.11)	-0.16 (0.10)	-0.19 (0.14)	-0.14 (0.09)

Table 2: *Mean SEABR amplitudes (μV) with SD for quiet and noise in each group*

Quiet vs. Noise

Trends seen with the mean latencies found in this study follow the predictable patterns that have been reported in previous electrophysiologic research. Overall peak latencies were prolonged for the noise conditions, as compared to the quiet conditions, with an individual peak latency shifts ranging from 0.2 msec (Wave F) to 0.95 msec (Wave O) for the NH group in the RE only condition versus 0.13 (Wave E) msec to 0.87 msec (Wave D) for the bilateral condition. The mean peak latency shift for the NH group for the RE only condition was 0.56 msec and 0.47 msec for the bilateral condition. The HL group had individual peak latency shift ranging from 0.06 msec (Wave E) to 0.41 msec (Wave A) for the RE only condition versus 0.02 msec (Wave F) to 0.41 msec (Wave D) for the bilateral condition. The mean peak latency shift for the HL group for the RE only condition was 0.22msec and 0.22 msec for the bilateral condition.

In addition, trends in peak amplitudes also proved to be consistent with previous research. Overall, the quiet conditions produced more robust waveforms than the noise conditions, with an individual peak amplitude increase ranging from 0.01 µV (Wave C) to 0.09 µV (Wave A) for the NH group in the RE only condition versus 0 µV (Wave C & F) to 0.13 µV (Wave D) for the bilateral condition. The mean peak amplitude increase for the NH group for the RE only condition was 0.04 µV and 0.05 µV for the bilateral condition. The HL group had individual peak latency shift ranging from 0 µV (Wave O) to 0.08 µV (Wave E) for the RE only condition versus 0 µV (Wave O) to 0.15 µV (Wave E) for the bilateral condition. The mean peak amplitude increase for the HL group for the RE only condition was 0.03 µV and 0.04 µV for the bilateral condition.

Figures 4, 5, 6 and 7 show four grand average waveforms illustrating the difference in latency and amplitude for the NH and HL participants in both quiet and noise. The waveforms represent an average across the entire waveform for all participants in these conditions. The waveforms in black show the responses in quiet, which are more robust than the noise response, in red, for each condition and group. In addition, Figures 5 and 7, which show the waveforms that were tested in the bilateral condition, are more robust than the waveforms that were tested in the RE only condition, as seen in Figures 4 and 6.

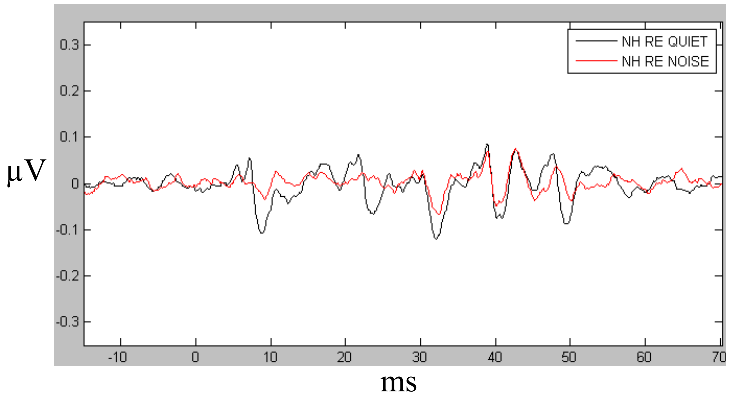

Figure 4: *Grand average waveform comparison of NH RE quiet condition versus NH RE noise condition.*

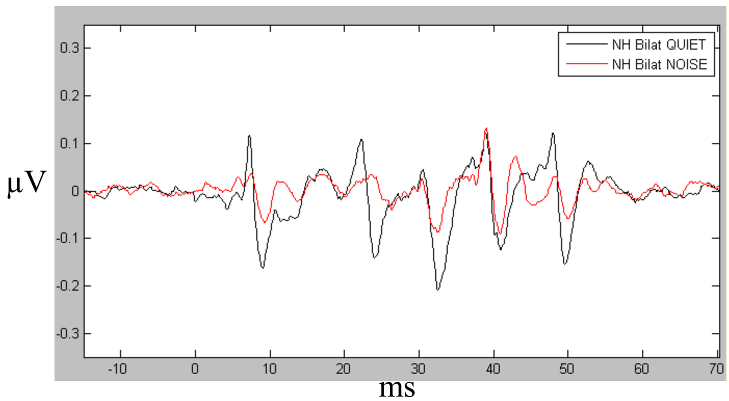

Figure 5: *Grand average waveform comparison of NH bilateral quiet condition versus NH bilateral noise condition.*

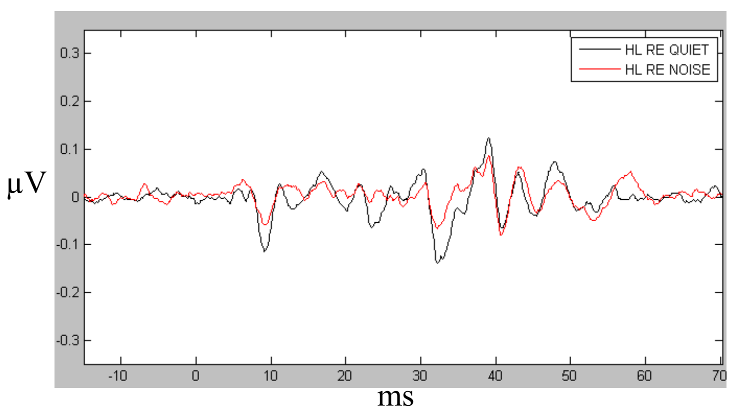

Figure 6: *Grand average waveform comparison of HL RE quiet condition versus HL RE noise condition.*

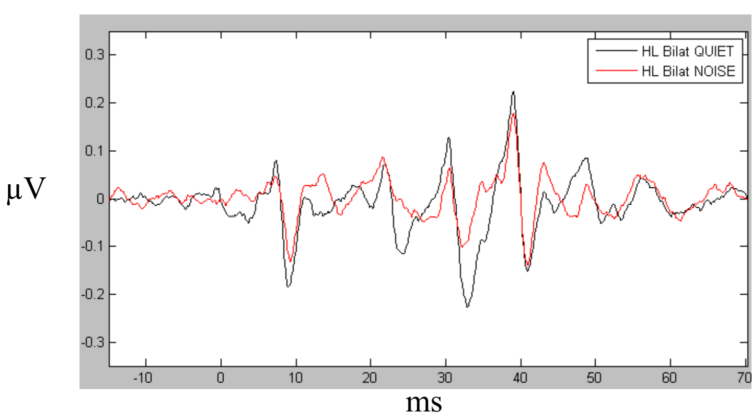

Figure 7: *Grand average waveform comparison of HL bilateral quiet condition versus HL bilateral noise condition.*

A repeated measure regression analysis was completed to assess if the quiet condition, as compared to the noise condition, had a significant effect on the latency and amplitude of the SEABR waveforms in the RE only and bilateral test conditions. The quiet vs noise effect is the overall difference between the quiet and noise conditions. For all analyses, effects were reported as significant at $p < 0.05$. Waves V, A, C, D and O were significant for latency in the bilateral condition. Waves V, A, D and E were significant for amplitude in the bilateral condition. Waves V, A, C, D, E and O were significant for latency in the RE only condition. Finally, Waves A, D, E and O were significant for amplitude in the RE only condition. The degrees of freedom and F-values for these significant findings are summarized in Table 3.

Condition	**Wave**	**df**	**F**
Latency Bilateral	V	1,15	41.342
	A	1,15	11.481
	C	1,12	15.496
	D	1,15	18.953
	O	1,15	5.690
Amplitude Bilateral	V	1,15	26.964
	A	1,15	26.757
	D	1,15	40.831
	E	1,16	28.288
Latency RE	V	1,13	7.407
	A	1,13	32.522
	C	1,12	11.878
	D	1,15	9.661
	E	1,16	12.310
	O	1,16	21.205
Amplitude RE	A	1,13	35.491
	D	1,15	27.161
	E	1,16	30.944
	O	1,16	5.897

Table 3: *Degrees of freedom and f-values for the significant quiet vs noise findings*

The spectral encoding of the sustained portion of the response (the area between Wave C and O) for three frequency regions and standard deviations are shown in Table 4 for each test condition.

	103-121 Hz (SD)	454-719 Hz (SD)	721-1155 Hz (SD)
NH RE Quiet	0.052 (0.017)	0.007 (0.003)	0.003 (0.001)
NH RE Noise	0.023 (0.012)	0.006 (0.002)	0.002 (0.001)
NH Bilat Quiet	0.076 (0.023)	0.009 (0.003)	0.003 (0.001)
NH Bilat Noise	0.034 (0.022)	0.008 (0.004)	0.003 (0.001)
HL RE Quiet	0.047 (0.020)	0.007 (0.004)	0.003 (0.001)
HL RE Noise	0.028 (0.018)	0.006 (0.004)	0.002 (0.001)
HL Bilat Quiet	0.094 (0.032)	0.010 (0.008)	0.003 (0.002)
HL Bilat Noise	0.055 (0.033)	0.008 (0.008)	0.003 (0.002)

Table 4: *Fast Fourier Transform analysis mean amplitude values and SD for three frequency ranges*

Figure 8 illustrates the degrading effect that noise has on the phase-locking properties of the response in the low frequencies. The spectrum in black shows the response in quiet, which is more robust than the noise response in red.

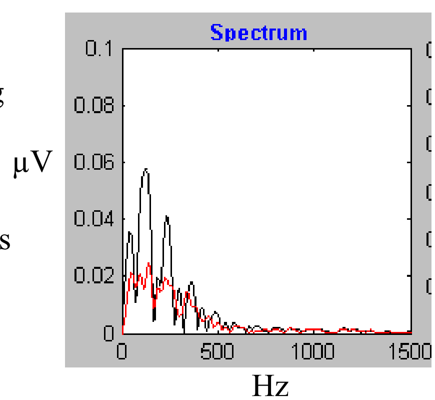

Figure 8: *Frequency spectrum for bilat quiet (black) vs bilat noise (red).*

FFT analysis showed that F_0 ($F_{(1,16)} = 82.865$; $p = 0.00$) was significant in the bilateral condition. In addition, F_0 ($F_{(1,16)} = 65.669$; $p = 0.00$), F1 ($F_{(1,16)} = 8.876$; $p = 0.010$) and F2 ($F_{(1,16)} = 25.417$; $p = 0.00$) were significant in the RE only condition.

The RMS amplitude of the response calculated for the sustained portion of the response was significant for amplitude in the bilateral condition ($F_{(1,16)} = 25.073$; $p = 0.00$) and for the RE only condition ($F_{(1,16)} = 76.409$; $p = 0.00$).

Quiet vs Noise by Group

Figure 9 shows a graphical comparison between the NH RE quiet grand average waveform and the HL RE quiet grand average waveform. Figure 10 shows a graphical comparison between the NH RE noise grand average waveform and the HL RE noise grand average waveform.

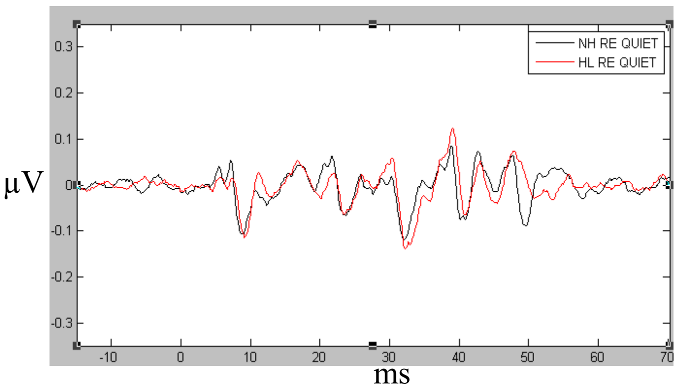

Figure 9: *Grand average waveform comparison of NH RE quiet condition versus HL RE quiet condition.*

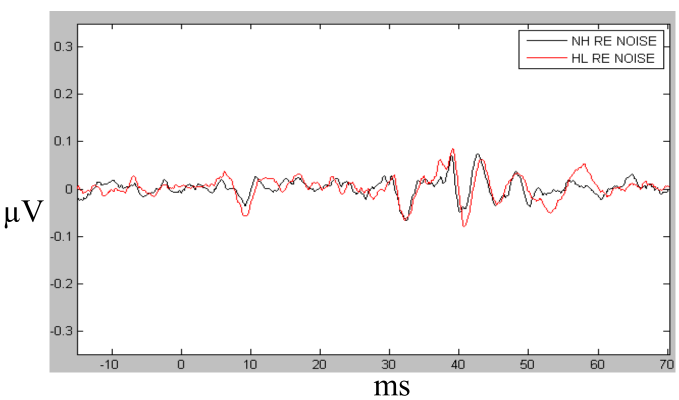

Figure 10: *Grand average waveform comparison of NH RE noise condition versus HL RE noise condition.*

The quiet vs noise by group interaction indicates whether the difference between the quiet and noise conditions is of different magnitudes for the NH and HL groups. A repeated measures regression analysis was completed to assess the group interaction.

Results showed a significant interaction for Wave E latency when the stimulus was presented to the right ear ($F_{(1,16)} = 12.310$; $p = 0.042$). Figure 11 shows that the relationship between the noise and quiet conditions was different based on hearing group. Wave E latency has a stronger relationship for the HL group. Noise appears to have a more detrimental effect on Wave E latency for the HL group; although, both groups had delayed latencies in the noise condition.

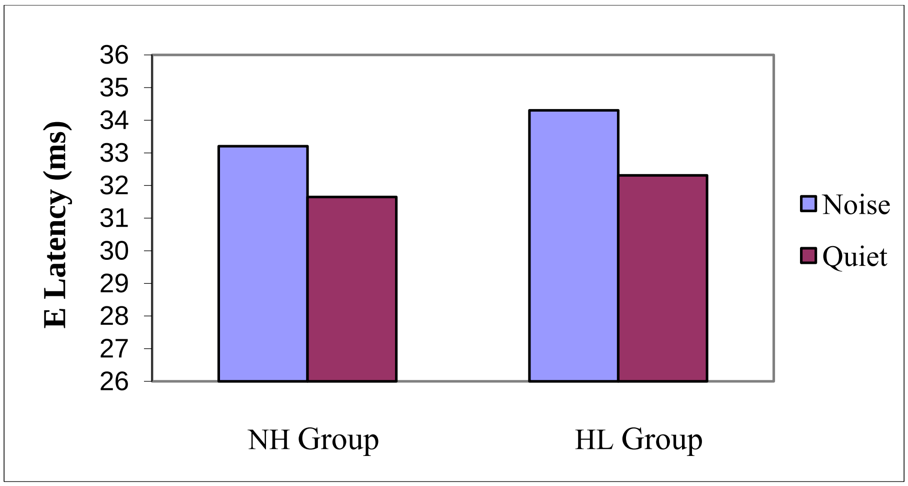

Figure 11: *Latency of Wave E by hearing group for SEABR noise and quiet conditions.*

Wave O latency ($F_{(1,16)} = 7.69$; $p = 0.015$) was significant when the stimulus was presented to the right ear. Wave O latency had a strong relationship for the NH group, but little relation for the HI group. Noise appears to have a more detrimental effect on Wave O latency for the NH group. The HI group, however, had delayed latencies for both noise and quiet conditions, compared to the NH group.

Wave F amplitude ($F_{(1,16)} = 11.146$; $p = 0.05$) was significant when the stimulus was presented to the right ear. Wave F amplitude had a stronger relationship for the HI group. Noise appears to have a more detrimental effect on Wave F amplitude for the HI group.

Wave O amplitude ($F_{(1,15)} = 4.667$; $p = 0.05$) was significant when the stimulus was presented bilaterally. Wave O amplitude had a strong relationship for the NH group, but little relation for the HI group. Noise appears to have a more detrimental effect on Wave F amplitude for the HI group.

There were no significant quiet versus noise by group interactions for the spectral encoding or RMS measures.

R-Space

The R-Space calculates a reception threshold for speech (RTS) score that represents the signal to noise ratio at 50% accuracy. Mean RTS score based on each participant's individual performance collapsed across session one and session two and the corresponding standard error bars are shown in Figure 12. NH participants had a mean score of -2.67 (SE = 0.16) in the RE only condition and -3.78 (SE = 0.37) in the bilateral condition. HL participants had a mean score of -0.33 (SE = 0.69) in the RE only condition and -2.44 (SE = 0.37) in the bilateral condition.

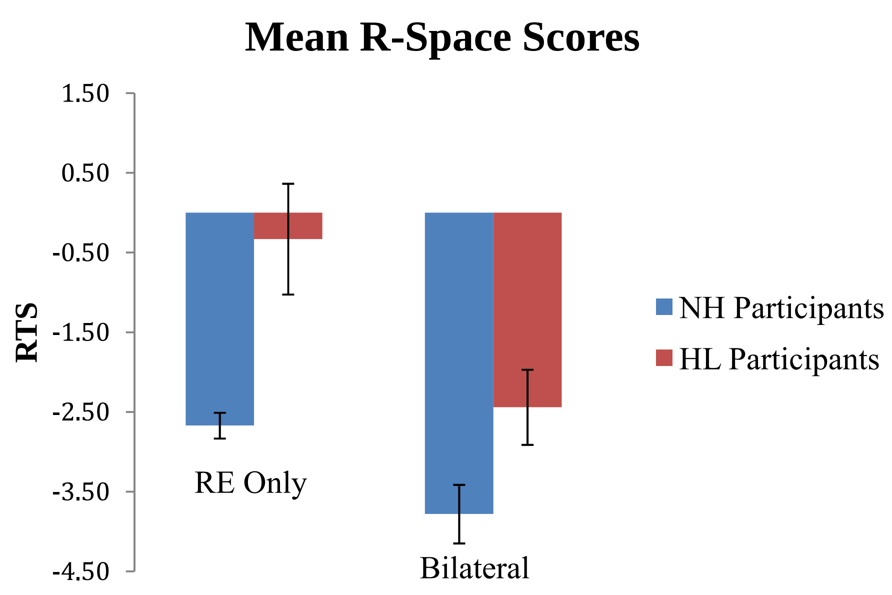

***Figure 12**: Mean R-Space data of session 1 and session 2 combined.*

A repeated measures multiple regression analysis was completed to assess if there was any significant difference in R-Space scores between the HL and NH group. Results showed the NH participant group had significantly better R-Space scores in the RE only listening condition ($F_{(1,16)} = 12.970$; $p = 0.002$) . In addition, the NH participant group had significantly better R-Space scores in the bilateral listening condition ($F_{(1,16)} = 6.135$; $p = 0.025$).

SEABR and R-Space Interactions

Quiet vs Noise by R-Space

The quiet vs noise by R-Space interaction designates whether the relationship of R-Space to the noise outcome is different from the relationship of R-Space to the quiet outcome. A repeated measures multiple regression analysis was completed to assess the group interaction. During analysis RE only SEABR data was compared to the RE only R-Space data and the bilateral SEABR data was compared to the bilateral R-Space data.

Results showed that the relationship between R-Space performance and Wave C latency ($F_{(1,12)} = 7.303$; $p = 0.022$) was significant when the stimulus was presented bilaterally. The low R-Space performers had earlier Wave C latencies than the high R-Space performers in both quiet and noise. The relationship between R-Space and Wave C latency in quiet was stronger than this relationship in noise.

The relationship between R-Space performance and Wave V amplitude ($F_{(1,15)} = 4.775$; $p = 0.048$) was significant when the stimulus was presented bilaterally. The high R-Space performers had a larger Wave V amplitude in quiet and noise. The relationship between R-Space and Wave V latency in quiet was stronger than this relationship in noise. Although, the high R-

Space performers did have a more robust Wave V amplitude in noise than the low R-Space performers.

The relationship between R-Space performance and Wave O amplitude ($F_{(1,16)} = 7.951$; $p = 0.014$) was significant when the stimulus was presented to the right ear only. In quiet, the relationship was stronger, with the high R-Space performers having a larger Wave O amplitude. In noise the participants with better R-Space performance also had a more robust response, but the relationship was not as strong.

The relationship between R-Space performance and spectral encoding of the F_O ($F_{(1,16)} = 4.712$; $p = 0.048$) was significant when the stimulus was presented bilaterally. Figure 13 shows that the participants with better R-Space scores encoded the F_0 more robustly in quiet and noise. The relationship between R-Space and encoding of the F_0 in quiet was stronger than this relationship in noise, so noise attenuates this relationship. However, the high R-Space performers do encode F_0 better than the low R-Space performers.

The relationship between R-Space performance and spectral encoding of the F_O ($F_{(1,16)} =5.273$; $p = 0.00$) was significant when the stimulus was presented to the right ear only. Figure 14 shows that in quiet all participants encoded the F_0 similarly. In noise, however, the participants with better R-Space performance encoded the F_0 more robustly. The relationship between R-Space and encoding of the F_0 in noise was stronger than this relationship in quiet, so noise is enhancing the relationship between R-Space and encoding of the F_0. Noise appears to have a more detrimental effect on encoding of the F_0 for the participants who perform poorer in the R-Space.

The relationship between R-Space performance and RMS amplitude ($F_{(1,16)} = 4.843$; $p = 0.045$) was significant when the stimulus was presented to the right ear only. Figure 15 shows that in quiet all participants had similar amplitude. In noise, however, the participants with better R-Space performance had a more robust response. The relationship between R-Space and RMS in noise is therefore, stronger than this relationship in quiet, so noise is enhancing the relationship between R-Space and RMS. Noise appears to have a more detrimental effect on encoding of the F_0 for the participants who perform poorer in the R-Space.

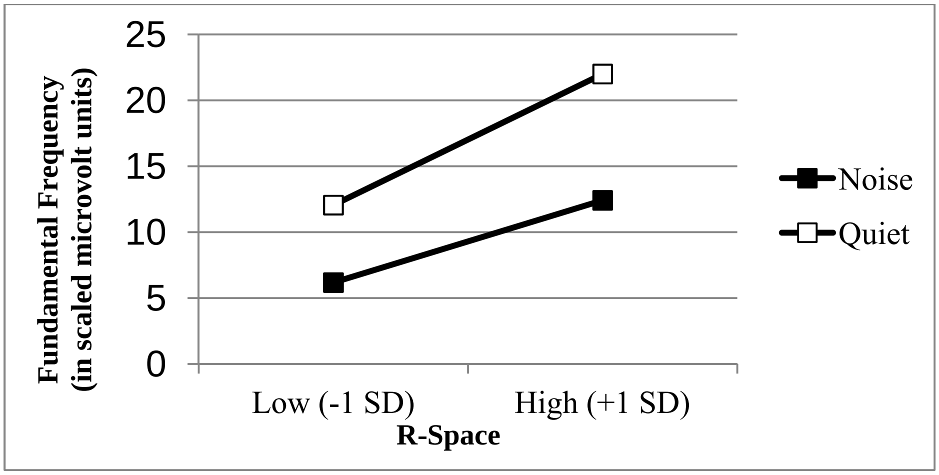

Figure 13: *Amplitude for the spectral encoding of the fundamental frequency (in scaled µV units) with the stimulus presented bilaterally as a function of R-Space performance measured bilaterally and SEABR listening conditions of quiet and noise (regression model for figure was based on R-Space RTS scores at +/- 1 SD).*

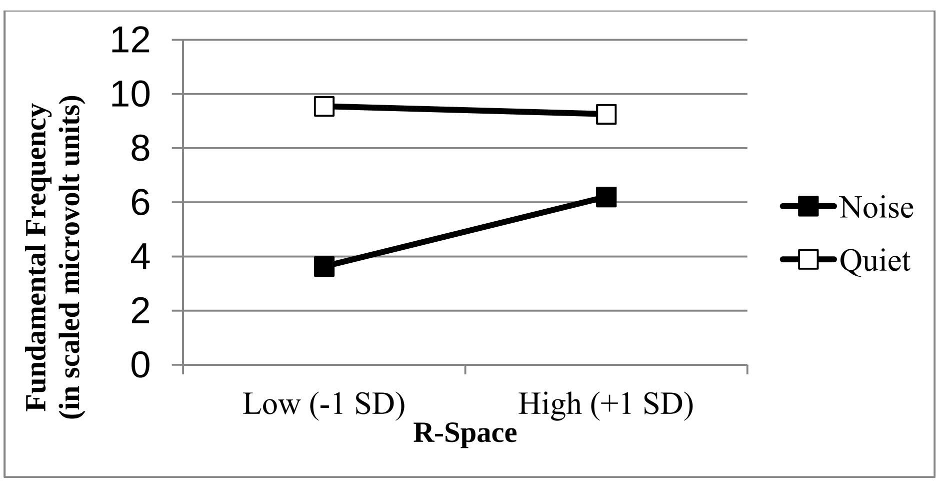

Figure 14: *Amplitude for the spectral encoding of the fundamental frequency (in scaled µV units) with stimulus presented in the right ear only as a function of R-Space performance measured in the right ear and SEABR listening conditions of quiet and noise (regression model for figure was based on R-Space RTS scores at +/- 1 SD).*

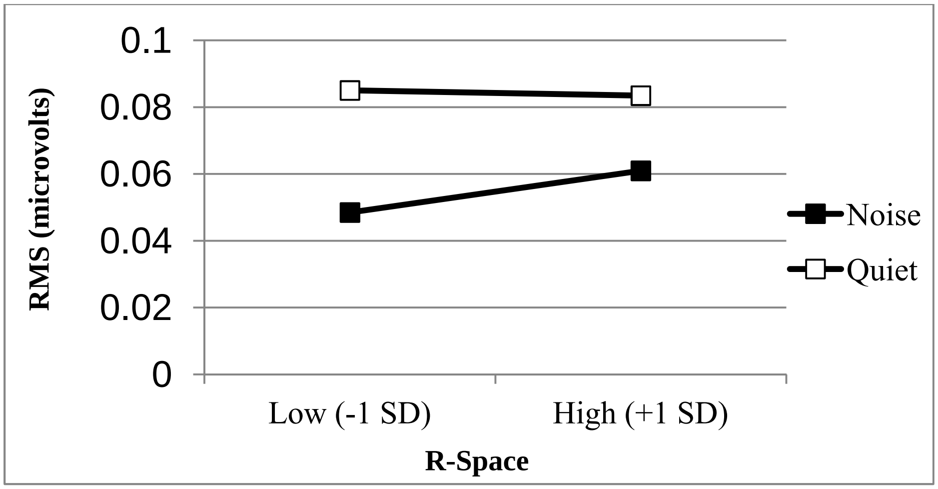

Figure 15: *Relationship between R-Space performance and RMS (in scaled µV units) amplitude when the stimulus was presented to the right ear only*

Quiet vs Noise by group by R-Space

The three-way interaction (quiet vs noise by group by R-Space) was also analyzed with a repeated measures multiple regression analysis. A significant interaction would indicate whether the difference in the R-Space relationship with quiet and with noise was different for the NH and HL participant groups. Results showed that there were no significant 3-way interactions.

DISCUSSION

Trends seen in the current study follow the predictable patterns that have been reported in previous electrophysiologic research. These effects were seen with both the NH and HL participant groups. The most robust waveforms were produced when the SEABR was measured bilaterally in quiet. More specifically, the quiet conditions produced more robust waveforms than the noise conditions and the bilateral conditions produced more robust waveforms than the RE only conditions. Overall peak latencies were prolonged for the noise conditions, as compared to the quiet conditions. Furthermore, the majority of individual peaks, in the quiet versus noise comparison, reached statistical significance for latency and amplitude for both RE and bilateral conditions. The reason that some peaks did not reach significance could be due to a small sample size or that different areas along the auditory pathways are affected more than others.

Statistically there were only a handful of significant differences for the quiet vs noise by group interaction. One possible reason is that the HL group had near-normal hearing thresholds in the low frequencies, which may not have created enough of a hearing difference between the two groups. In addition, it may be possible because all test stimuli were presented at a suprathreshold level, the HL group may have had a certain degree of recruitment and therefore they perceived the stimuli louder and thus resulting in more equivalent perception between the two groups.

To summarize, the findings of the current study support the idea that a relationship exists between SIN performance and the neurophysiologic response of the SEABR. Results showed that the relationship between the R-Space and the SEABR noise condition was different from the relationship between the R-Space and the SEABR quiet condition, for specific outcome measures. Notably, this relationship was seen to affect the sustained spectral portion of the F_0, which supports that a link exists between poor speech in noise performance and decreased magnitudes and spectral encoding of the fundamental and low frequencies.

The findings from Anderson et al. (2011) paralleled those of the current study, as they found that the bottom SIN performing group had decreased magnitudes for the F_0 and lower RMS amplitudes as compared to the top SIN group, which suggests the importance of F_0 encoding for successful SIN performance. The Anderson et al. study participants were older than those in the present study.

Song et al. (2011) also investigated the relation between SIN perception and the neural representation of the F_0 in the brainstem, this time in younger adults. They found that although background noise weakened the F_0 amplitudes in both top and bottom SIN performers, bottom performers were more greatly affected which corresponds to the findings in both the Anderson (2011) study and the current study.

Future research directions include examination of differences between monaural and binaural stimulation. This study showed interesting differences between the right ear and bilateral test conditons. There has been research that showed latency and amplitude differences for SEABR responses with right ear only and left ear only stimulation (Hornickely et al., 2009; Vander Werff and Burns, 2011). Research comparing monaural to binaural stimulation, as was done in this study is needed. In addition, this study only tested individuals with an overall mild to moderate hearing loss. It is feasible that different degrees of hearing loss or configurations would produce changes in the neural response. A large scale study with hearing-impaired individuals who varied by configuration and magnitude of hearing loss would add to the understanding of the effect of hearing loss on neural responses at the level of the brainstem.

REFERENCES

Akhoun, I., Gallego, S., Moulin, A., Menard, M., Veuillet, E., Berger-Vachon, C., Collet, L. & Thai-Van, H. (2008). The temporal relationship between speech auditory brainstem responses and the acoustic pattern of the phoneme /ba/ in normal-hearing adults. *Clinical Neurophysiology*. *119*(4); 922-933.

Anderson, S., Clark, A., Yi, H., & Kraus, N (2011). A neural basis of speech in noise perception in older adults. *Ear Hearing*. 32(6):750-7.

Anderson, S., Skoe, E., Chandrasekaran, B., & Kraus, N (2010 A). Neural timing is linked to speech perception in noise. *Journal of Neurosciences*, 30:4922-4926.

Anderson, S., Skoe, E. Chandrasekaran, B., Zecker, S. & Kraus, N. (2010 B) Brainstem correlates of speech-in-noise perception in children. *Hearing Research.* 1;270(1-2):151-7.

Best, V., Mason, C. & Kidd, G. (2011) Spatial release from masking in normally hearing and hearing-impaired listeners as a function of the temporal overlap of competing talkers. *Journal of Acoustical Society of America.* 129(3):1616-25.

Carhart R, Jerger J. (1959) Preferred method for clinical determination of pure tone thresholds. *Journal of Speech & Hearing Disorders* 24:330-345.

Compton-Conley, C., Neuman, A. Killion, M. & Levitt, H. (2004). Performance of Directional Microphones or Hearing Aids: Real-World versus Simulation. *Journal of American Academy of Audiology*. 15:440–455.

Cunningham, J., Nicol, T., King, C. Zecker, S. & Kraus, N. (2002) Effects of noise and cue enhancement on neural responses to speech in auditory midbrain, thalamus and cortex. *Hearing Research*. 169:97-111.

Cunningham, J., Nicol, T., Zecker, S. G., Bradlow, A., & Kraus, N. (2001). Neurobiologic responses to speech in noise in children with learning problems: deficits and strategies for improvement. *Clinical Neurophysiology, 112*(5):758-767.

Dubno, J., Dirks, D. & Morgan, D. (1984) Effects of age and mild hearing loss on speech recognition in noise. *Journal of the Acoustical. Society of America* 76(1):87-96

Eisenberg, L., Dirks, D. & Bell, T. (1995) Speech recognition in amplitude-modulated noise of listeners with normal and listeners with impaired hearing. *Hearing Research.* 38(1):222-33.

Hornickel, J., Skoe., E. & Kraus, N. (2008) Subcortical laterality of speech encoding. *Audiology and Neurotology.* 14: 198-207

Johnson, Nicol & Kraus. (2005) Brain stem response to speech: a biological marker of auditory processing. *Ear and Hearing.* 26(5):424-434.

Kraus N & Nicol T. (2005) Brainstem origins for cortical "what" and "'where" pathways in the auditory system. *Trends in Neurosciences* 28:176-181.

Pressnitzer, Sayles, Micheyl, & Winter. (2008) Perceptual organization of sound begins in the auditory periphery. *Current Biology* 18:1124-8.

Revit, L., Schulein, R. & Julstrom, S. (2002) Toward Accurate Assessment of Real-World Hearing Aid Benefit. *Hearing Review.*

Ruggles, D., Bharadwaj, H. & Shinn-Cunningham, B. (2011) Normal hearing is not enough to guarantee robust encoding of suprathreshold features important in everyday communication. *PNAS.* 108(37):15516-15521

Russo N., Nicol T., Musacchia G., & Kraus, N. (2004) Brainstem responses to speech syllables. *Clinical Neurophysiology* 115:2021-2030.

Song, J. H., Banai, K., Russo, N. M., & Kraus, N. (2006). On the relationship between speech- and nonspeech-evoked auditory brainstem responses. *Audiology and Neurotology.* *11*(4):233-241.

Song, J.H., Nicol, T., and Kraus, N. (2010) Test-retest reliability of the speech-evoked auditory brainstem response. *Clinical Neurophysiolog.* 122(2):346-55.

Song, J., Skoe, E., Banai, K., and Kraus N (2011). Perception of speech in noise: neural correlates. *Journal of Cognitive Neuroscence.* 23(9):2268-79.

Vander Werff, K. & Burns, K. (2011) Brainstem responses to speech in younger and older adults. *Ear and Hearing*. 32: 168-180.