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Speech-evoked auditory brainstem response in children with unilateral hearing loss

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SPEECH-EVOKED AUDITORY BRAINSTEM RESPONSE IN CHILDREN WITH UNILATERAL HEARING LOSS

by

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Abstract:

Speech-evoked auditory brainstem responses (ABRs) and speech recognition measures were evaluated in children with unilateral hearing loss (UHL) and normal hearing (NH). There were significant differences between the two hearing groups for several components of the response in quiet and in noise. Children with UHL performed worse than children with NH on all speech recognition measures in quiet and in noise.

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Introduction

There are distinct advantages to having two normal hearing (NH) ears. First, listening with two ears allows the perception of sound to be louder compared to listening with one ear alone; this is known as the binaural summation effect (Epstein & Florentine, 2012; Fletcher & Munson, 1933). With binaural summation, two inputs of the same signal are received instead of one which allows for improved speech intelligibility (Ching, Incerti, Hill and van Wanrooy, 2006). Second, the ability to understand speech in a noisy setting is assisted by both the head shadow effect (Shaw, 1974) and binaural squelch (Carhart, 1965; Middlebrooks & Green, 1991). The head shadow effect (Shaw, 1974) allows for selective attention to the ear with a better signal-to-noise ratio (SNR) in background noise; it is a physical phenomenon due to the size and location of the head. Binaural squelch requires binaural processing and reflects the brain's ability to use inter-aural time and phase differences between competing signals to reduce the impact of noise on speech perception (Carhart, 1965). Finally, having two ears aides in the ability to localize a sound source (Kuhn, 1977; Wightman & Kistler, 1992).

Unilateral hearing loss (UHL) modifies the organization of the auditory system due to monaural rather than binaural input (Firszt, Ulmer, & Gaggl, 2006; Ponton et al., 2001; Vasama & Makela, 1995). UHL also results in multiple barriers to communication. Adults report difficulty identifying the location of sounds, hearing soft speech, and understanding speech in noisy environments (Andersen, Shcroder, & Bonding, 2006; Firszt, Holden, Reeder, Waltzman, & Arndt, 2012; McLeod, Upfold, & Taylor, 2008; Welsh, Welsh, Rosen, & Dragonette, 2004). Recently, Rothpletz, Wightman, and Kistler (2012) measured speech recognition in noise and localization abilities in adults with UHL and those with NH. Spatial cues were assessed in the speech recognition in noise task by having the target and masker in the same location as well as spatially separated. The participants with UHL had significantly worse speech recognition in noise compared to NH listeners; the inability to utilize spatial cues was thought to be most detrimental to the performance of those with UHL.

Although adults with UHL report these strains on communication, the degree varies greatly from one person to another. Welsh, Welsh, Rosen and Dragonette (2004) studied speech recognition in noise using single words (Northwestern University Auditory test 6; Tillman & Carhart, 1966) in quiet and at a +10 SNR with speech babble. Adults with UHL had a decrease in noise compared to quiet between 0-60%, with an average decrease of 34%. Adults who also had UHL but in addition, a high frequency sensorineural hearing loss in their better ear, had score decreases anywhere from 4-72%, with an average decrease of 42%. Performance was highly variable in both participant groups, suggesting the degree of hearing loss was only one contributing factor to poor speech recognition in noise. However, Welsh et al. were unable to find a relationship between the participants' speech recognition in noise performance and their age of onset of hearing loss or length of deafness.

Previous studies have demonstrated that children with UHL experience breakdowns in communication, delayed language development, and academic difficulties (Bess, Tharpe & Gibler, 1986; Culbertson & Gilbert, 1986; Klee & Davis, 1986; Lieu, Tye-Murray, & Fu, 2012). Children with UHL had poorer word recognition, spelling, and language scores compared to their NH peers (Culbertson & Gilbert, 1986). Culbertson and Gilbert's results suggest UHL, especially when the poorer ear has a severe-to-profound hearing loss, may be associated with cognitive and academic deficits, as well as secondary behavioral problems. Children with UHL also had significantly worse language comprehension, oral expression, and oral composite scores compared to their NH siblings (Lieu, Tye-Murray, Karzon, & Piccirillo, 2010). In addition, Lieu and colleagues found that children with UHL were more likely to have special education and speech-language services in school. Including NH siblings of children with UHL in their study allowed for the control of several variables, such as socioeconomic status, environment, and genetic factors. Lieu and colleagues found that UHL independently predicted poor oral language scores, and that family income and maternal education were also factors.

Lieu, Tye-Murray, and Fu (2012) examined whether oral language skills and educational performance improved over time in children with UHL. Although children showed an improvement in oral language skills as measured by standardized tests, both school records and teacher narrative reports documented no significant improvement in academic performance over the three year study period. Lieu, Tye-Murray and Fu’s results suggest that the academic performance of children with UHL depend on factors other than oral language skills alone.

Children with NH differ substantially in their speech recognition in noise abilities compared to children with UHL. Utilizing the Nonsense Syllable Test (Levitt & Resnick, 1978) children with UHL performed significantly poorer in noise compared to their NH peers; at a -10 SNR children with UHL averaged 35% correct whereas children with NH averaged 49% correct (Bess, Tharpe, & Gibler, 1986). When assessing speech recognition in noise using the Hearing in Noise Test - Children (HINT-C), children with UHL required a SNR advantage of 2.23 dB (zero degrees azimuth) and 7.67 dB (target directed to poorer ear) to perform as well as children with NH (Ruschetta, Arjmand, & Pratt, 2005).

Bess, Tharpe, and Gibler (1986) also analyzed their data to determine whether ear of deafness contributed to differences in performance. Although not significant, their analysis showed a trend for children with right ear deafness to perform more poorly than children with left ear deafness. Hartvig Jensen, Borre and Johansen (1989) further examined ear of deafness effects and found significant differences between children who were right ear deaf compared to children with either left ear deafness or NH. Specifically, children with right ear deafness exhibited poorer performance on verbal and nonverbal tests.

Although behavioral deficits have been identified, few studies have examined the neural processing of speech in children with UHL. The auditory brainstem response (ABR) has proven to be a clinically useful tool for assessing neural function at the brainstem level and is most commonly elicited by clicks or tone-bursts. However, recent research has established that complex stimuli can also elicit the response. Music, complex tones, and speech stimuli (e.g., /da/, /ba/, and /ga/) have been used to elicit an ABR. A speech stimulus is particularly useful, as it can provide cues as to how temporal and spectral features are preserved in the brainstem (Skoe & Kraus, 2010). Understanding neural processing at the brainstem level may assist in understanding outcomes in varied populations such as individuals with hearing loss, language disorders, and learning deficits. Although several complex stimuli have been used to elicit the ABR, speech (specifically /da/) has most commonly been used.

When elicited with the stimulus /da/, the subcortical response emerges as a waveform of seven identifiable peaks, labeled V, A, C, D, E, F, and O. This response is known as the speech-evoked ABR. Waves V and A reflect the onset of the response, wave C the transition region, waves D, E, and F the periodic region (i.e., the frequency following response), and wave O the offset of the response (Skoe & Kraus, 2010).

The speech-evoked ABR is a repeatable and reliable objective measure (Hornickel, Knowles and Kraus, 2012; Russo, Nicol, Musacchia and Kraus, 2004; Song, Nicol and Kraus, 2011). Song, Nicol and Kraus (2011) examined test-retest reliability of the speech-evoked ABR in young adults (ages 19-36) over a one month period. They found no significant effects of session on the latency and amplitude of any peaks. Hornickel, Knowles and Kraus (2012) investigated the test-retest reliability of the speech-evoked ABR in children ages 8-13 over a one year period. Again, no significant differences in latency, amplitude, or spectral encoding of the response were observed in the span of a year suggesting that the speech-evoked ABR was reliable and had reached maturation in this age group.

The speech-evoked ABR provides a physiologic representation of poor speech encoding evident in children with language, literacy, reading, and learning deficits (Banai et al., 2009; Johnson, Nicol, Zecker, & Kraus, 2007; King, Warrier, Hayes, & Kraus, 2002). Children with known language-based learning problems exhibited delayed latencies for waves C and O (Johnson, Nicol, Zecker, & Kraus, 2007) and wave A (King, Warrier, Hayes, & Kraus, 2002) compared to their normal learning peers. In addition, children who were poorer readers tended to have prolonged latencies, poorer waveform morphology, and weaker spectral encoding compared to children who were better readers (Banai et al., 2009; Hornickel, Anderson, Skoe, Yi, & Kraus, 2012). These studies show a trend that difficulties in language, literacy, reading, and learning affect the subcortical representation of speech and that delayed response latencies tend to be associated with these difficulties.

The speech-evoked ABR has also been studied with stimuli presented in noise. The addition of ipsilateral noise predominately affected the presence of the onset of the response (waves V and A) and also resulted in a reduction of amplitude for all waves (Johnson, Nicol, & Kraus, 2005; Russo, Nicol, Musacchia & Kraus, 2004). However, noise was less degrading to the frequency following response (waves D, E, and F) which retained presence and did not shift in latency with the addition of background noise (Johnson, Nicol, & Kraus, 2005). Prevost, Laroche, Marcoux and Dajani (2013) examined subcortical responses to the vowel /a/ with ipsilateral noise in adults. Results for the vowel /a/ were similar to that of the consonant-vowel /da/; the addition of ipsilateral noise increased latency and reduced amplitude of the response onset. Prevost and colleagues concluded that noise appears to degrade the onset of the stimulus regardless if the stimulus was a consonant-vowel (/da/) or vowel (/a/).

In addition, new studies have investigated the relation between the speech-evoked ABR in noise and behavioral speech recognition in noise measures in typically-developing children. As expected, the addition of noise delayed the neural response, but children who were poorer with speech recognition in noise had significantly delayed latencies compared to children who performed better in noise (Anderson, Skoe, Chandrasekaran, & Kraus, 2010). Other studies have shown associations between the speech-evoked ABR and both reading ability and speech recognition in noise; better reading ability and speech recognition in noise correlated with more robust neural responses (Hornickel, Chandrasekaran, Zecker, & Kraus, 2011). However speech recognition in noise and reading ability were not related, which suggests that reading and speech recognition in noise have two distinct neural pathways involved in processing sound.

One of the biggest complaints of people with hearing loss and other auditory processing disorders is the increased difficulty understanding speech among background noise (Kochkin, 2000; Moore, 2003). The speech-evoked ABR may be used as a tool to objectively measure and quantify the effects of noise, and may shed light on why some people have more difficulty in noise than others. Anderson, Parbery-Clark, White-Schwoch and Kraus (2013) examined if the speech-evoked ABR in adults could predict self-reported speech recognition in noise ability by using the Quick Speech-in-Noise test (QuickSIN; Killion, Niquette, Gudmundsen, Revit, & Banerjee, 2004) and the Speech Spatial and Qualities of Hearing Qualities scale (SSQ; Gatehouse & Noble, 2004). The latency of the offset (wave O) and overall morphology of the response significantly contributed to the prediction of self-reported speech recognition in noise ability, even more so than QuickSIN results or age.

The overall purpose of the current study was to investigate speech recognition in noise abilities and the speech-evoked ABR in children with UHL and NH. Investigation of auditory evoked potentials in this population will provide new information about how sound, and speech in particular, is neurally encoded at the brainstem when the auditory system relies on single ear input and how the encoding compares to individuals with NH in both ears. Specifically, the objectives of the present study were to 1) evaluate the reliability of the speech-evoked ABR in children with UHL and a control group of NH age-matched peers, 2) assess the effects of noise on the speech-evoked ABR in children with UHL and NH, 3) evaluate speech recognition in noise in both study groups, and 4) assess the relation, if any, between behavioral measures of speech recognition and the neural response. The respective hypotheses were: 1) the speech-evoked ABR recorded from children with UHL and NH is reliable across test sessions, 2) ipsilateral noise will degrade response morphology and prolong latencies for both groups (responses from the +5 SNR condition will be more affected than the +10 SNR condition), responses from children with UHL will show greater degradation than children with NH, 3) children in both groups will have similar speech recognition scores in quiet, however children with UHL will have poorer scores in noise, 4) the degree of amplitude change for F0 (fundamental frequency) in noise versus quiet will negatively correlate with behavioral speech recognition in noise scores; that is, children with greater F0 degradation in noise will have poorer speech recognition in noise scores.

Methods

Participants

Twenty-four children ages 7-17 years participated in the study. Twelve children had UHL (mean age 12.6 years, standard deviation [SD] 2.5 years; 7 males, 5 females), and 12 children had NH (mean age 12.9, SD 3.1), who were age and gender matched to the participants with UHL. For the purposes of this study, NH is defined as having pure tone air conduction thresholds of 30 dB HL or better from 500-4000 Hz. UHL is defined as having one NH ear and one ear with a moderately severe or greater hearing loss from 500-4000 Hz. All of the participants with UHL had a sensorineural hearing loss except one participant who had a maximum conductive hearing loss due to atresia. Children with known learning disabilities were excluded. Demographic information for the NH and UHL participants is shown in Tables 1 and 2. Study procedures received institutional review board (IRB) approval through the Human Research Protection Office at Washington University in St. Louis; participants were compensated for their time and travel.

Procedure

All participants were seen for two test sessions with a maximum time between sessions of five weeks. Test sessions were 1-2 hours each. Except for the initial hearing test, the order of the other procedures varied for ease of scheduling and to help maintain the participant's attention and interest. Testing measures were counter-balanced to prevent order and learning effects.

Audiometric Levels. Audiometric air conduction thresholds were obtained to confirm eligibility for the study and to document hearing levels. Air conducted thresholds were obtained at octave intervals from 250-8000 Hz with inter-octaves at 3000 and 6000 Hz presented through supra-aural headphones. The participant was instructed to raise a hand or press a button each time the tone was heard, even when the tone was just barely audible.

Electrophysiologic measures. Participants were seated in a comfortable chair in a single-walled sound treated booth. In order to create a wakeful and relaxing state, the participant either played on an iPad™ or watched a DVD of his/her choice on a portable DVD player with captions and the audio muted. The participant was not asked to respond in any way, but rather to relax and focus on the DVD. Participants with UHL listened in their everyday listening mode while participants with NH listened with both ears simultaneously through ER-3A or ER-3B insert earphones. To record brainstem responses, three reusable gold cup electrodes were attached with medical tape and recorded using a one-channel electrode montage with Cz as input 1, left earlobe as input 2, and right earlobe as ground. Responses were recorded using the Bio-logic Navigator Pro AEP v7.0 system with BioMARK v2.0 software.

A click-evoked ABR was obtained for each participant to verify normal function of the neural pathway, and was completed at both the first and second test sessions. Click-evoked responses were obtained monaurally in the right ear and left ear for participants with NH, and in the NH ear for participants with UHL. The click stimulus was 100µs in duration and the response was recorded at 80 dBnHL using rarefaction polarity and a 13.3/second stimulus rate. 2000 sweeps were collected and repeated to verify wave presence, and waves I, II, III, IV, and V were identified on the superimposed raw waveforms.

The speech-evoked ABR was completed at both the first and second test sessions. Speech-evoked ABRs were obtained binaurally for participants with NH, and in the NH ear for participants with UHL. The stimulus was presented at 80 dB SPL in three listening conditions: quiet, and with pink noise at a +10 and +5 signal-to-noise-ratio (SNR). For the participants with

NH, the pink noise was presented binaurally; for the participants with UHL, the pink noise was presented ipsilaterally. Conditions were randomized for each participant at each test session. The stimulus was a five-formant synthesized /da/ that was 40 milliseconds in duration with an inter-stimulus interval of 51 milliseconds. Two trials of 3000 sweeps were collected for each listening condition. Both trials were averaged to create a calculated wave of 6000 sweeps. A total of three calculated waves were generated at the first test session, and all conditions were repeated at the second test session.

Speech recognition measures. Single syllable words, the Consonant-Nucleus-Consonant test, or CNC (Peterson & Lehiste, 1962) were presented via a loud speaker facing the participant in a double-walled sound treated booth at each test session. The words were presented at 60 dB SPL in two listening conditions: in quiet, and with background noise (4-talker babble) at a +8 SNR. The participant repeated each word, and was encouraged to guess if unsure. In addition, the Hearing In Noise Test (HINT) sentences, (Nilsson, Soli, & Sullivan, 1994) were administered adaptively in the presence of restaurant noise (R-SPACE™; Revit, Schulein, & Julsrom, 2002; Compton-Conley et al., 2004) at 60 dB SPL. The level of the sentences varied from approximately 8-10 dB louder than the noise to approximately 6-10 dB softer than the noise based on participant responses. The participant was seated in the center of an eight loud speaker 360° array. Sentences were presented from the front speaker and restaurant noise from the other surrounding speakers. The participant was asked to repeat each sentence, guessing if unsure and passing if unable to guess.

Questionnaire. Parents of the participants completed a modified version of the Speech, Spatial and Qualities of Hearing Scale (SSQ). The original questionnaire was designed for adults with emphasis on binaural hearing ability (Gatehouse & Noble, 2004; Noble & Gatehouse, 2004). The modified version, the Speech, Spatial and Qualities of Hearing Scale for Parents of Children with Impaired Hearing was specifically designed for parents of children with hearing loss (Galvin, Hughes & Mok, 2010). The SSQ has 22 questions that are divided into three sections: speech hearing, spatial hearing, and quality of hearing. For each question a listening situation is described and the parents rate their child’s performance on a scale from 0-10, with 0 being “Not at all” (least ability) and 10 being “Perfectly” (greatest ability).

Data analysis

A total of six waveforms (two in quiet, two at +10 SNR, two at +5 SNR) were analyzed for each participant. Seven prominent waves were identified per waveform: V, A, C, D, E, F, and O. Two individuals with experience analyzing speech-evoked ABR measures determined wave presence/absence for all recorded waveforms. Data were converted to a text file and imported to the Brainstem Toolbox (Skoe & Kraus, 2010) using MATLAB vR2009b. Latency and amplitude values across all conditions and peaks were assessed. The latency, amplitude, area, and slope between waves V and A (known as the V/A complex) were also analyzed. The frequency components of the response were analyzed using a fast Fourier transform (FFT) in three frequency regions (F0=103-121 Hz, F1=454-719 Hz, F2=721-1155 Hz). Data were analyzed using repeated measures analysis of variance (ANOVA) to evaluate the effects of session (reliability), group (NH vs UHL) and listening condition (quiet vs +10 SNR vs +5 SNR) on the speech-evoked ABR waves and for the SSQ results (domains and group). Bonferroni post hoc comparisons were conducted when appropriate. T-tests were used to assess group (NH vs UHL) effects for the behavioral measures (CNC words in quiet, CNC words in noise, HINT sentences presented in R-SPACE™). Pearson correlations identified whether relations existed between behavioral measures and demographic variables (e.g. length of deafness). Significance for all analyses was determined at $p < 0.05$.

Results

Audiometric Levels

Figure 1 shows audiometric thresholds for both ears of the NH and UHL participants. The mean and SD three-frequency pure tone average (PTA) for the NH group was 2 dB HL (SD 2 dB) for the right ear and 3 dB HL (SD 4 dB) for the left ear. For the UHL participants, the mean and SD for the good ear was 6 dB HL (SD 4 dB) and for the poor ear 98 dB HL (SD 22 dB).

Reliability

Figure 2 shows raw tracings of the click-evoked ABR for session one (in black) and session two (in gray) for one NH participant and one participant with UHL. Waves I through V are prominent and repeatable for both individuals at both sessions. Figure 3 shows the mean Wave V latency of the click-evoked ABR for the NH and UHL groups. A two (group) by two (session) repeated measures ANOVA indicated there was not a significant session effect ($F(1,22) = 1.82$, $p > 0.05$) nor was there a significant group effect ($F(1,22) = 0.55$, $p > 0.05$).

Figure 4 illustrates raw speech-evoked ABR tracings for session one (in blue) and session two (in green) in quiet for one NH participant and one participant with UHL. Below each individual tracing is a no stimulation waveform. Latency (in msec) for Waves V, A, C, D, E, F and O is shown on the x-axis and amplitude (in µV) is displayed on the y-axis. The superimposed waveforms show the consistent repeatability when recorded at two different sessions for an individual. The reliability of the speech-evoked ABR was assessed using the following results at each session: latency and amplitude of waves V, A, C, D, E, F, O, and the

V/A complex; slope and area of the V/A complex; and amplitude of the three frequency regions. Given each component was recorded in three conditions, that of quiet, +10 SNR and +5 SNR, there were 63 variables (latency of seven waves, three conditions; amplitude of seven waves, three conditions; V/A latency, three conditions, V/A amplitude, three conditions, V/A slope, three conditions, V/A area, three conditions; three frequency regions, three conditions). ANOVAs and Bonferroni corrected post hoc comparisons indicated that 61 out of 63 speech-evoked ABR components were not significantly different between sessions ($ps > 0.05$), which suggests that the speech-evoked ABR was highly reliable. In addition, 57 of 63 components were not significantly different between the NH and UHL groups ($ps > 0.05$).

Effects of Noise

Grand average waveforms were calculated for all participants in each group (NH and UHL) and illustrate the averages of all raw waveforms per group. Figure 5 shows the grand averages for both groups for each of the three conditions: quiet, +10 SNR and +5 SNR. Waves V, A, C, D, E, F and O are identified when present. Repeated measures ANOVAs indicated there was a significant effect of listening condition for latency and amplitude of each wave, the three frequency regions, and the V/A complex slope and area. Post-hoc comparisons showed the quiet condition was significantly different from the +10 SNR condition for 19 of 21 components (17/19 $ps < 0.001$), as was the quiet condition versus the +5 SNR (again, 19 of 21 significant component differences, 18/19 $ps < 0.001$). There were fewer significant differences for the +10 versus +5 SNR condition (7 of 21 significant components, 3/7 $ps < 0.001$). Latency increased and amplitude decreased with the addition of either +10 or +5 SNR compared to quiet, with fewer differences noted between the two noise conditions. Figure 6 illustrates the effects of noise on latency and amplitude for one example wave, that of Wave D. As the amount of noise increased, latencies increased for each condition; amplitudes were reduced in noise compared to the quiet condition. These effects were observed for all wave components for both NH and UHL groups.

Effects of Hearing Group

Figure 7 shows the mean latency or amplitude of the components that were significantly different between the participants with UHL and NH ($p < 0.05$). In the quiet condition (panel A), the amplitude of V, A, O, V/A slope and V/A area were significantly different between groups (ps < 0.05). In the +10 SNR condition (panels B and C), significant group differences were for the amplitude and latency of wave O. In the +5 SNR condition (panels D and E), amplitude of wave D and the area of the V/A complex were significantly different between groups as was the latency of wave D. Finally, the frequency region F0 was significantly different between hearing groups in the quiet condition (panel F); the frequency region F2 was again significantly different between groups in the +10 SNR condition (panel G). For all but one component (latency of wave D in the +5 condition) participants with NH had significantly earlier latencies and larger amplitudes compared to participants with UHL ($p < 0.05$).

Speech Recognition Measures

Figure 8 shows group mean speech recognition scores and individual data for CNC words in quiet and noise for the NH and UHL groups. A two (group) by two (noise condition) repeated measures ANOVA identified a significant main effect of noise condition ($F(1, 22) = 148.22$, $p < 0.001$), and a significant main effect of group ($F(1, 22) = 17.04$, $p < 0.001$). A paired samples T-test showed mean scores to be significantly higher for the NH group than the UHL group (CNC words in quiet, $t(22) = 4.50$, $p < 0.001$; CNC words in noise, $t(22) = 3.63$, $p < 0.001$). In addition, both groups performed significantly better in quiet than in noise (NH, $t(11) = 8.94$, $p <$

0.001; UHL, $t(11) = 8.42$, $p < 0.001$). There was a significant group by noise condition interaction ($F(1, 22) = 5.49$, $p < 0.05$) indicating that the condition effect differed between the groups. Specifically, the UHL group showed a greater decrease in noise than the NH group. Individual data showed greater variability among the UHL participants when noise was present compared to the NH participants.

Figure 9 displays the group and individual data for the HINT sentences presented in R-SPACE™; again the NH groups' mean reception threshold for sentences (RTS) was significantly lower (better) than the UHL group ($t(22) = -3.68$, $p < 0.001$). Individual data showed great variability among both groups, however participants with NH seemed to vary more in their mean RTS compared to participants with UHL. Despite this variability, nine of the NH participants' RTS were better than -3 dB compared to only two of the UHL participants.

SSQ Questionnaire

Group means and individual data for the SSQ are depicted in Figure 10. A two (group) by three (domain) repeated measures ANOVA identified a significant main effect of group, $F(1,21) = 65.00$, $p < 0.001$, and significant domain effect, $F(1.46, 30.59) = 17.71$, $p < 0.001$. There was also a significant group by domain interaction, $F(1.46, 30.59) = 13.85$, $p < 0.001$, indicating that the domain effect differed between the two groups. Follow-up analysis indicated SSQ ratings for the three domains (speech, spatial, and quality) were significantly different between groups ($ps < 0.001$). For children with NH, there was no difference between the three domains ($p > 0.05$). For children with UHL, there was a significant difference between the speech and spatial domains ($p < 0.001$), the qualities and spatial domains ($p < 0.001$), but not between the speech and qualities domains ($p > 0.05$).

Correlations Between Speech-evoked ABR Components and Behavioral Measures

Several variables were evaluated to determine whether relations existed between the speech-evoked ABR components and behavioral measures. Results from Pearson analyses including all participants showed that correlations were moderate but significant for CNC word scores in noise and two speech-evoked ABR components: the amplitude of wave V in the +5 SNR condition (.422, $p = 0.05$) and the fundamental frequency in the +5 SNR condition (.423, $p = 0.039$). No other wave components in either noise condition were significantly correlated with CNC word scores in noise and no correlations were found between the variables and scores on the HINT sentences presented in R-SPACE™. No significant relations were found when the participant groups were evaluated separately.

Correlational analyses were also conducted between responses on the SSQ, speech recognition measures, and demographic variables. No statistically significant correlations were found when collapsed across groups between the three sections of the SSQ and speech recognition in noise measures, length of deafness, age at test, or hearing sensitivity. CNC word scores in quiet were significantly correlated with the SSQ speech domain ($p < 0.05$) for children with UHL. In contrast, all three sections of the SSQ significantly correlated with CNC word scores in noise ($p < 0.05$) for children with NH.

Discussion

The purpose of the current study was to investigate speech recognition in noise abilities and the speech-evoked ABR in children with UHL and NH. The aims of the present study were to 1) evaluate the reliability of the speech-evoked ABR in children with UHL and a control group of NH age-matched peers, 2) assess the effects of noise on the speech-evoked ABR in children with UHL and NH, 3) evaluate speech recognition in noise in both study groups, and 4) assess the relation, if any, between behavioral measures of speech recognition and the neural response.

Reliability

In the current study, responses were reliable across test sessions for all participants for both the click-evoked and speech-evoked ABR. This was expected for the click-evoked ABR since it is considered a repeatable objective measure. The speech-evoked ABR was also highly reliable for both groups when recorded both in quiet and noise. These results agree with previous speech-evoked ABR studies in children using stimuli in quiet and noise (Hornickel, Knowles & Kraus, 2012; Song, Nicol & Kraus, 2011).

Effects of Noise

Click-evoked ABRs were not significantly different between groups ($p > 0.05$), however groups significantly differed for some components of the speech-evoked ABR. For both children with UHL and NH, ipsilateral noise degraded response morphology, prolonged latencies and reduced amplitudes. Just as predicted, there was a significant difference in latency and amplitude of each wave between the quiet condition and the +10 SNR condition, and the quiet condition and the +5 SNR condition. Fewer differences in latency and amplitude were found between the +10 SNR and +5 SNR conditions, suggesting that the addition of 5 dB of noise does make an impact, but not in a different manner than adding +10 dB of noise. Although the effect of noise was observed for NH and UHL groups, each participant seemed to have their own “signature” response with slightly varied morphology. Interestingly, their respective individual characteristics present in the quiet condition were maintained with the addition of noise.

Effects of Hearing Group

Differences between children with UHL and children with NH were noted for all three conditions. In noise, the differences occurred for the amplitudes and latencies of waves D (at +5 SNR) and O (at +10 SNR), VA area (at +5 SNR), and the amplitude of F2 (at +10 SNR). In all cases except one, children with UHL had significantly longer latencies and smaller amplitudes compared to children with NH. The latency of wave D in the +5 SNR condition was shorter for children with UHL compared to children with NH. Wave D represents the beginning of the frequency following response, and wave O the offset. The significant differences between groups for these two areas of the response suggests that in noise neural encoding of the vowel (the frequency following response) and the offset was more difficult for children with UHL compared to children with NH.

It is important to note that ear of stimulation differed between groups. For the children with UHL, click-evoked and speech-evoked ABRs were stimulated in the good hearing ear. For children with NH, speech-evoked ABRs were stimulated binaurally. Two children with UHL had normal to moderate low-frequency hearing sensitivity and were stimulated binaurally as well as monaurally. Figures 11 and 12 show binaural versus right ear stimulation for three children with NH and the two children with UHL. The tracings for the NH participants (Figure 11) show clear increases in amplitude for the binaural versus monaural recordings which is evident across the entire waveform in quiet (larger responses in green versus red) and most of the waveform in noise with the exception of N12. This pattern is not as evident in Figure 12 where the same conditions are shown for the two UHL participants. In particular, U6 shows substantially larger responses in the right ear alone condition compared to that of binaural. It is possible that the groups speech-evoked ABRs differ due to binaural versus monaural stimulation rather than unilateral hearing loss per se. However, children with UHL hear and encode sound neurally with just one ear, thus the monaural condition reflects their everyday listening mode and their speech ABRs reflect their ability to encode sound in quiet and noise with unilateral input.

Speech Recognition Measures

Statistical analysis revealed significant differences between groups for all behavioral measures, even CNC words presented in quiet. Participants in both groups performed better in quiet than in noise, however participants with UHL performed significantly worse in noise compared to participants with NH. In addition, participants with UHL were more variable in their CNC word scores in noise than participants with NH. In agreement with this finding, results were similar for the HINT sentences presented in R-SPACE™; participants with NH performed better than participants with UHL. These results for speech stimuli in noise agree with the predicted hypotheses and the notion that children with UHL are at a disadvantage in noisy settings. Monaural input makes it difficult to effectively hear and understand what is being said in the presence of background noise.

SSQ Questionnaire

SSQ ratings were significantly different between groups in all three domains: speech, spatial, and quality. There was no difference between the three domains for the participants with NH. However, there was a significant difference between domains for the participants with UHL. As predicted, the parents of children with UHL rated their childs’ spatial performance most affected by their hearing loss. However, there was a considerable variability between the parents’ responses - some parents reported their children to have great difficulty locating the source of sounds, whereas other parents reported their children to have sufficient abilities. The SSQ scores were analyzed to determine whether a relation existed with either age, length of deafness, or hearing sensitivity. None of these correlations were significant.

Correlations Between Speech-evoked ABR Components and Behavioral Measures

There were two correlations identified between the speech-evoked ABR and speech recognition measures. CNC words in noise scores were correlated positively with the amplitude of wave V and the fundamental frequency, both at the +5 SNR condition. In other words, higher scores for CNC words in noise were related to larger amplitudes of wave V and the fundamental frequency. These correlations were only apparent when including all participants; no relationships were found regarding hearing group.

Summary

In summary, the present study found the speech-evoked ABR to be reliable across test sessions in children with UHL and NH. Noise degraded response morphology, reduced amplitudes and increased latencies in both groups. There were a number of components in specific conditions that significantly differed in amplitude and/or latency between groups, with the participants with NH usually having larger amplitudes and/or shorter latencies. Speech recognition in noise was markedly different between groups, even in quiet; children with NH performed better than children with UHL. SSQ ratings differed between groups; however there was a significant difference between the three domains for the participants with UHL, with the spatial domain being ranked the lowest. Finally, modest correlations were found between some of the speech-evoked ABR components and behavioral measures in noise.

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Participant	Gender	AAT (years)	AAOPHL (years)	AAI (years)	LOD (years)	Poorer Ear	Etiology	HA Use
U1	M	10	0	birth	10	Left	Atresia	Baha
U2	M	9	7	7	2	Left	Sudden SNHL	Baha
U3	F	13	0*	1.5	13	Left	Unknown	HA at school
U4	M	14	2	2	12	Left	Traumatic Brain Injury	FM at school
U5	M	13	4	4	9	Left	Unknown	FM at school
U6	M	15	0*	8	15	Left	Unknown	None
U7	M	8	0*	5	8	Left	Unknown	None
U8	F	13	0*	4	13	Left	Unknown	None
U9	F	16	0*	2.5	16	Right	Unknown	Baha
U10	F	13	0*	3	13	Right	Mondini malformation	None
U11	F	12	0*	5	12	Left	Unknown	None
U12	M	15	2	2	13	Left	Meningitis	FM at school
Mean		**12.6**			**11.3**			
SD		*2.5*			*3.7*			

Table 1. Demographic information for participants with UHL. Gender, age at test (AAT), age at onset of profound hearing loss (AAOPHL), age at identification (AAI), length of deafness (LOD), poorer ear, etiology and hearing aid (HA) use are listed for each participant. * denotes presumed congenital.

Participant	**Gender**	**AAT (years)**
N1	F	12
N2	M	13
N3	M	11
N4	M	8
N5	M	14
N6	M	16
N7	F	13
N8	F	14
N9	M	7
N10	F	14
N11	M	17
N12	F	16
Mean		**12.9**
SD		*3.1*

Table 2. Demographic information for participants with NH. Gender and age at test (AAT) are listed for each participant.

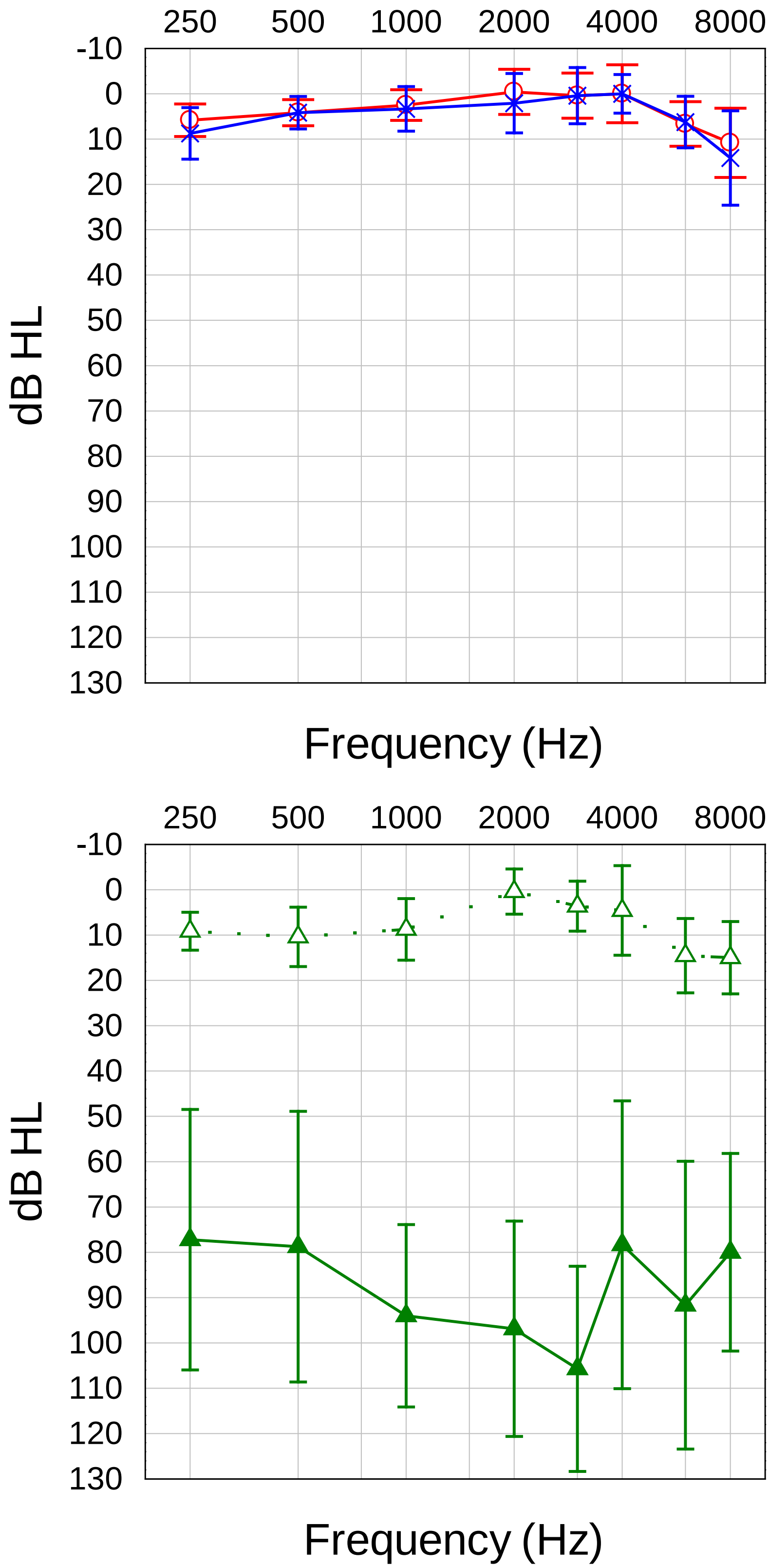


Figure 1. Mean pure-tone air conduction thresholds for participants with NH (top) and participants with UHL (bottom) from 250-8000 Hz. Error bars equal one standard deviation.

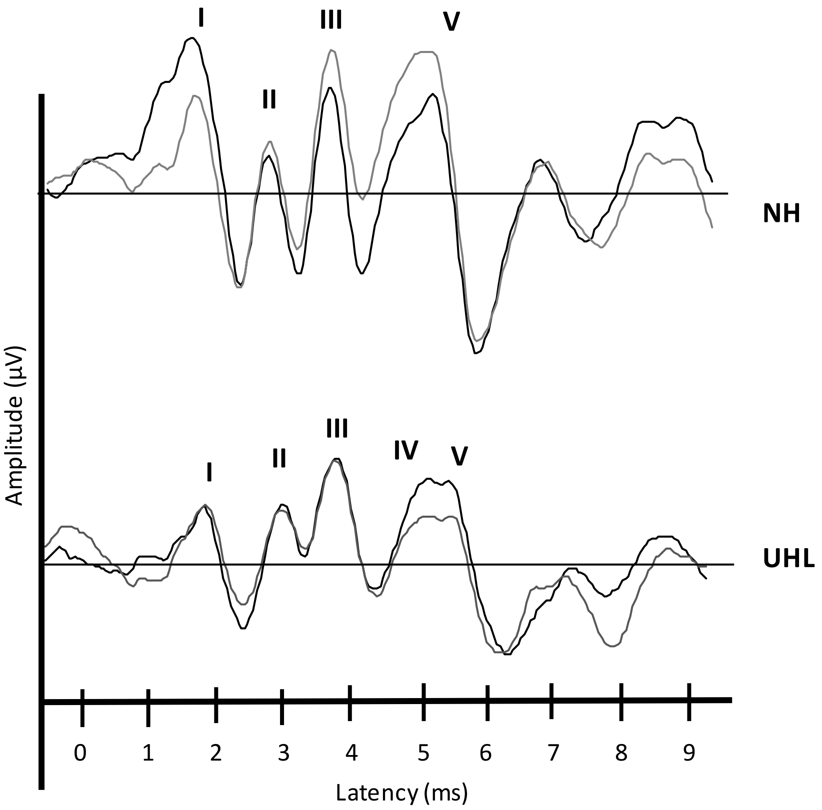


Figure 2. Click-evoked ABR raw tracings of one participant with NH and one participant with UHL. Session one is in black, session two is in gray.

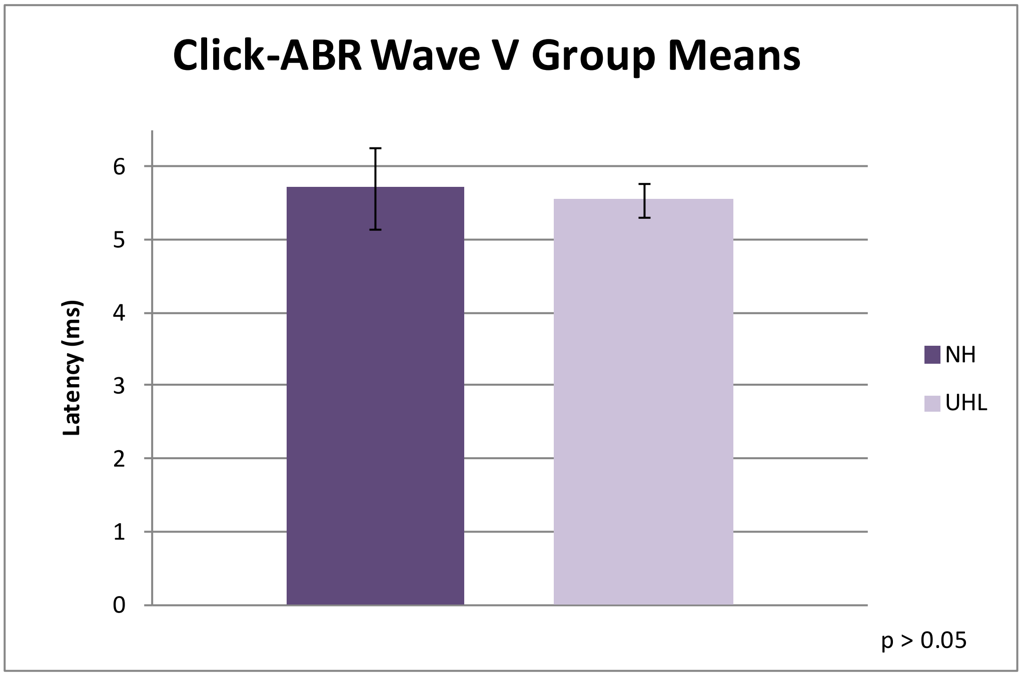


Figure 3. Mean latency in msec of wave V of the click-evoked ABR for participants with NH and UHL. Error bars equal one standard deviation.

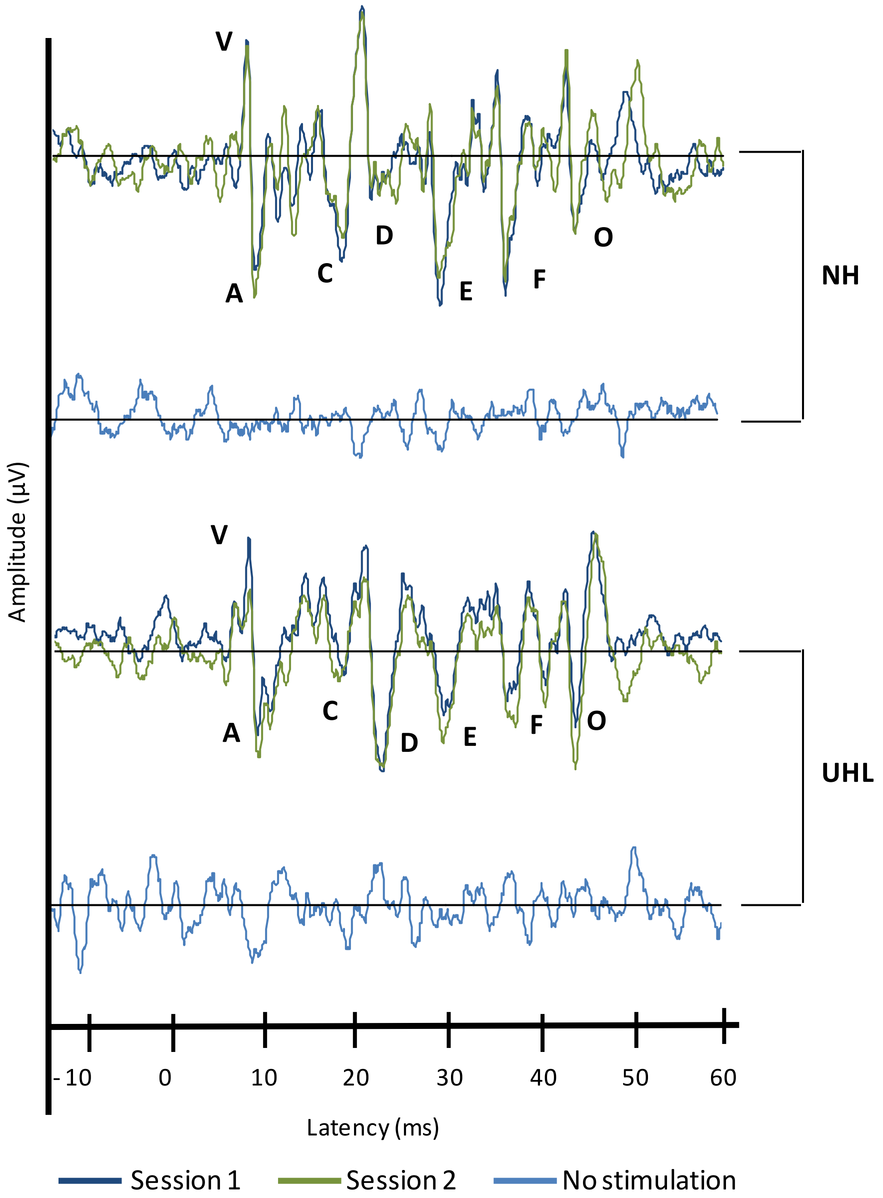


Figure 4. Speech-evoked ABR raw tracings and no stimulation waveforms of one participant with NH and one participant with UHL. Session one is in dark blue, session two is in green, and no stimulation is in light blue.

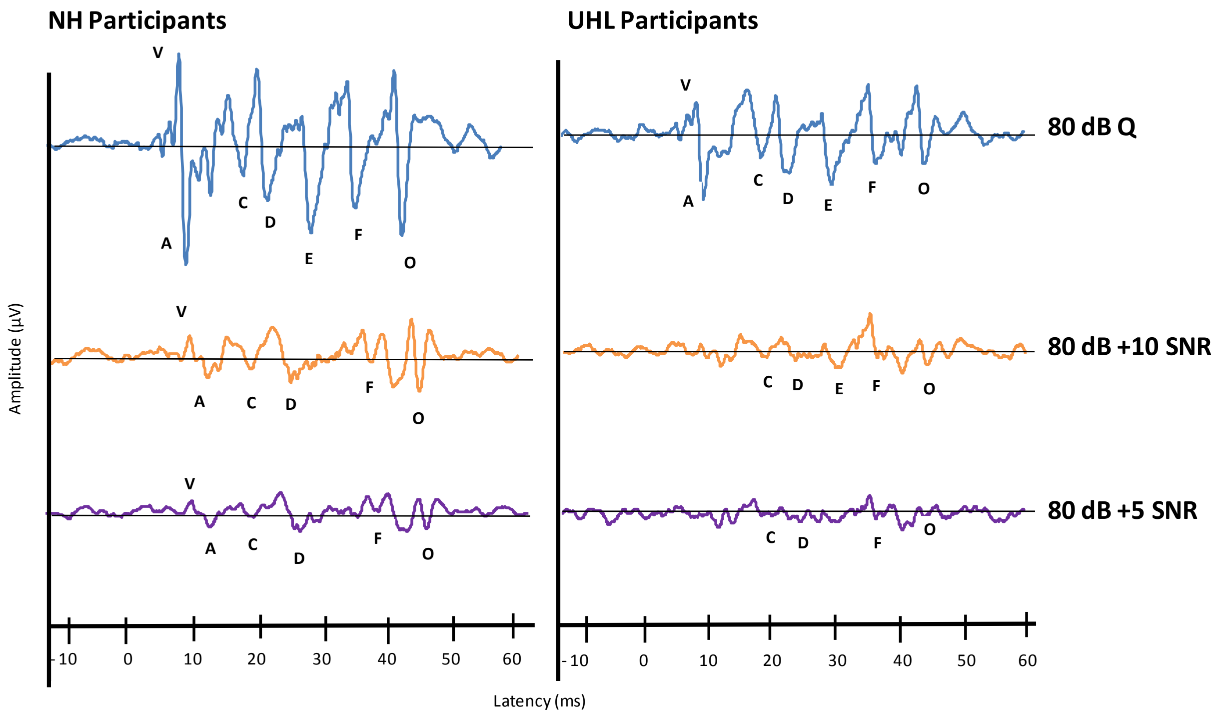


Figure 5. Grand average waveforms for both NH and UHL groups. Waves V, A, C, D, E, F, and O are labeled, if present. Responses are shown in quiet (blue), at +10 SNR (orange) and at +5 SNR (purple).

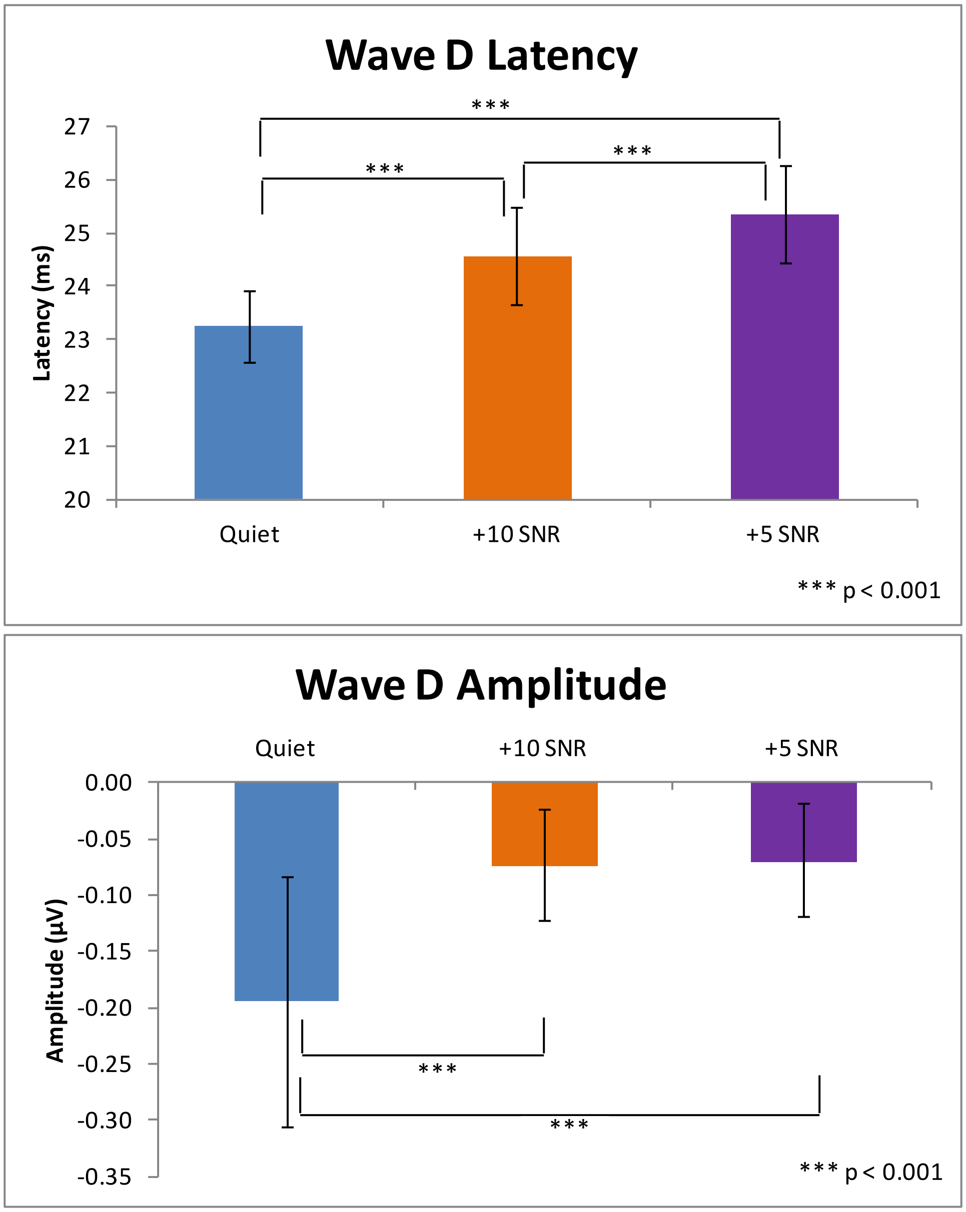


Figure 6. Mean latencies (top panel) and amplitudes (bottom panel) combined across groups in quiet, +10 SNR and +5 SNR of the speech-evoked ABR wave D. Error bars equal one standard deviation.

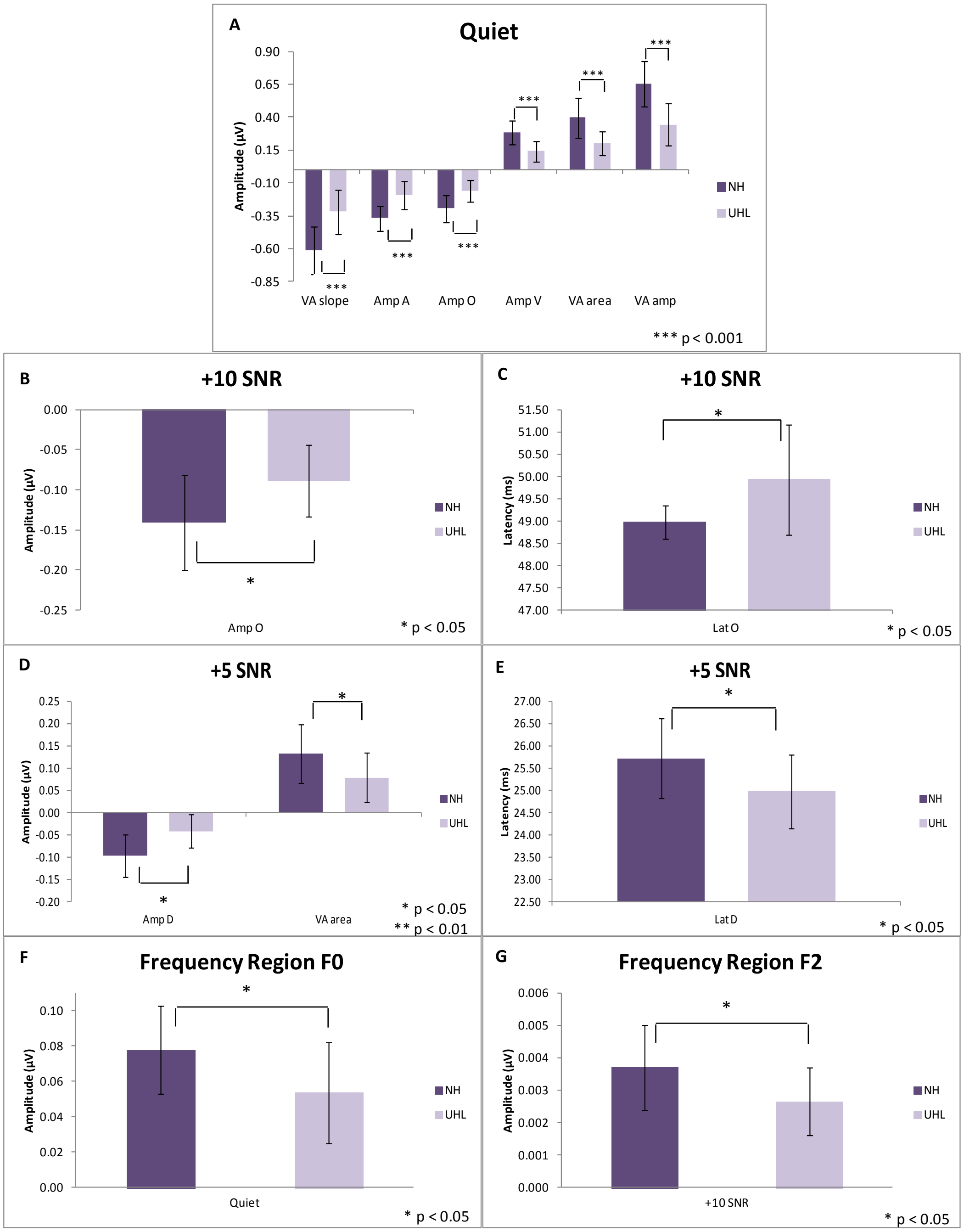


Figure 7. Speech-evoked ABR components that were significantly different between hearing groups (ps < 0.05). Panel A: group amplitude differences in the quiet condition; panel B: group amplitude differences in the +10 SNR condition; panel C: group latency differences in the +10 SNR condition; panel D: group amplitude differences in the +5 SNR condition; panel E: group latency differences in the +5 SNR condition; panel F: group amplitude differences of F0 in the quiet condition; panel G: group amplitude differences of F2 in the +10 SNR condition. Error bars equal one standard deviation.

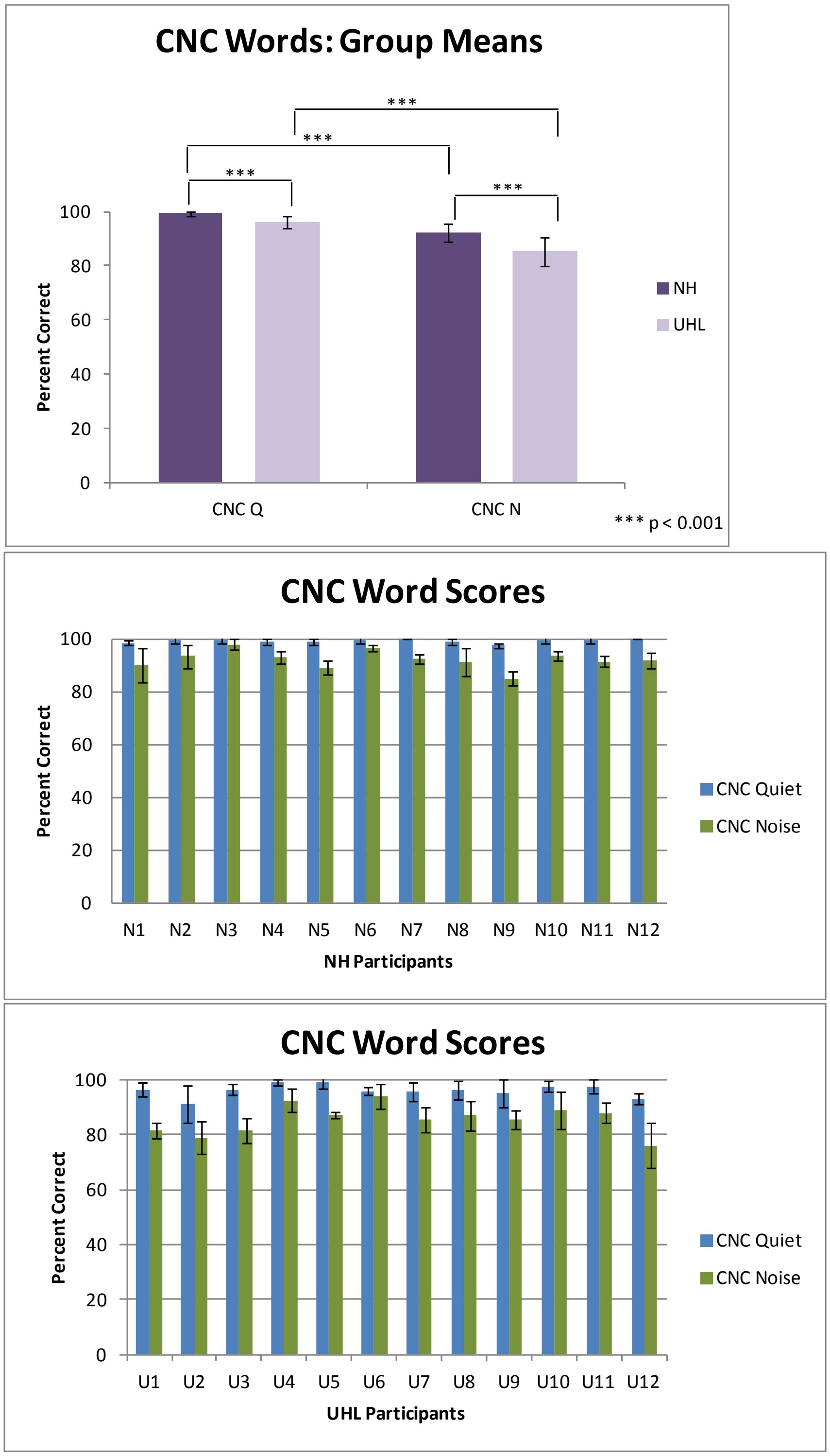
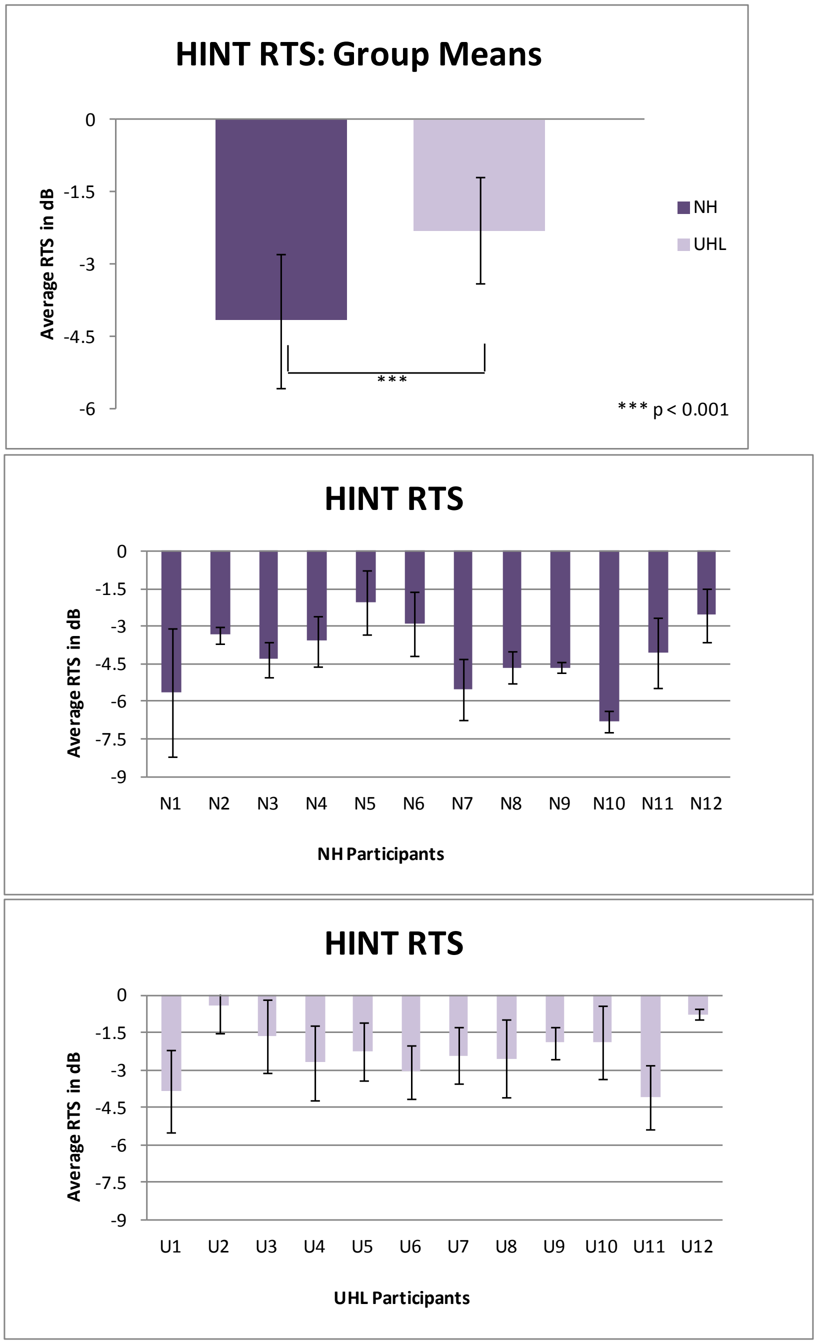


Figure 8. Group means and individual data for CNC word scores in quiet and in noise for NH and UHL participants. Error bars equal one standard deviation.



HINT RTS: Group Means

HINT RTS

HINT RTS

Figure 9. Group means and individual data for HINT sentences presented in R-SPACE™ for NH and UHL participants. Error bars equal one standard deviation.

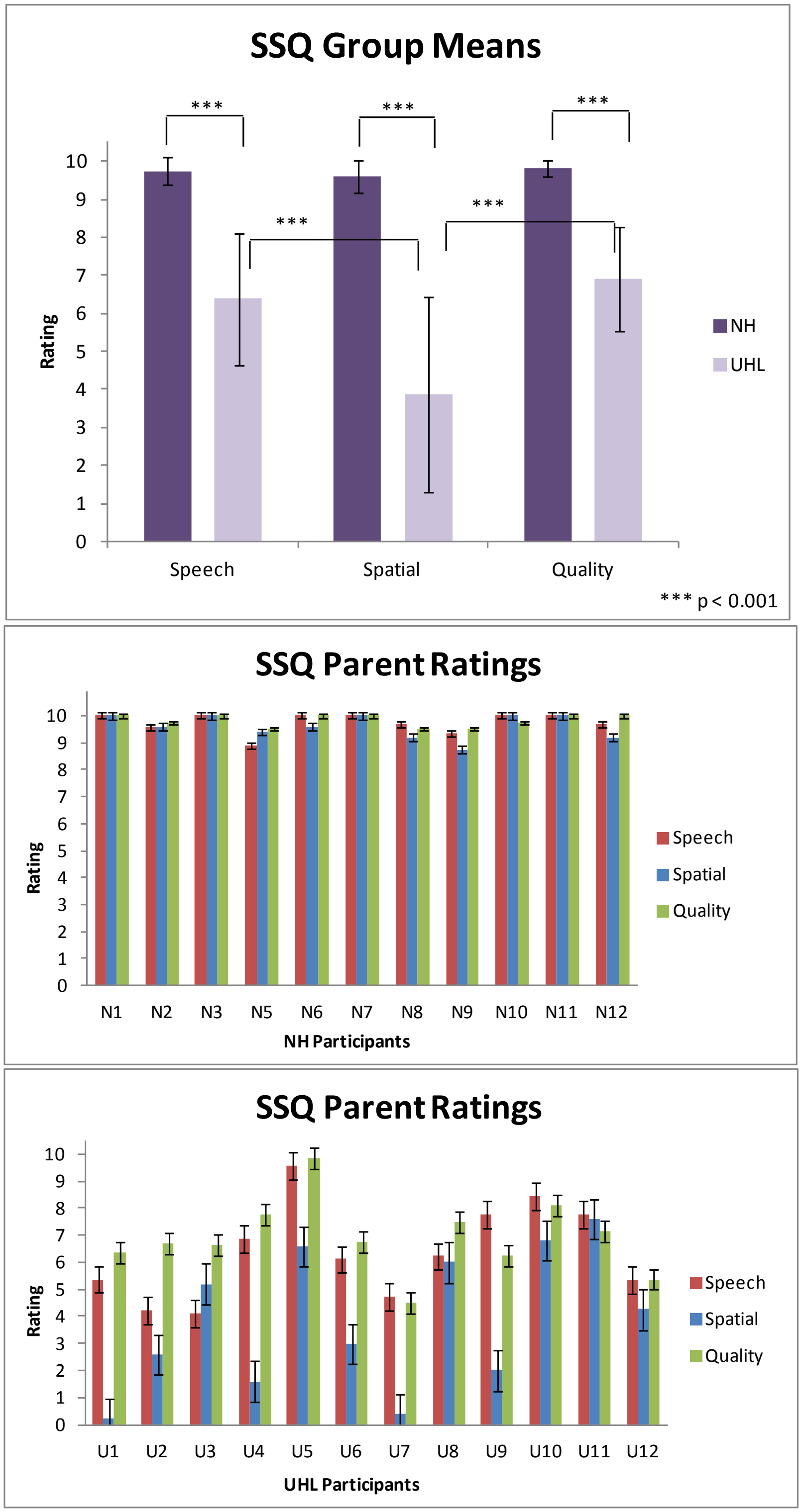


Figure 10. Group means and individual SSQ results for NH and UHL participants for each domain: speech, spatial, and quality. Error bars equal one standard error.

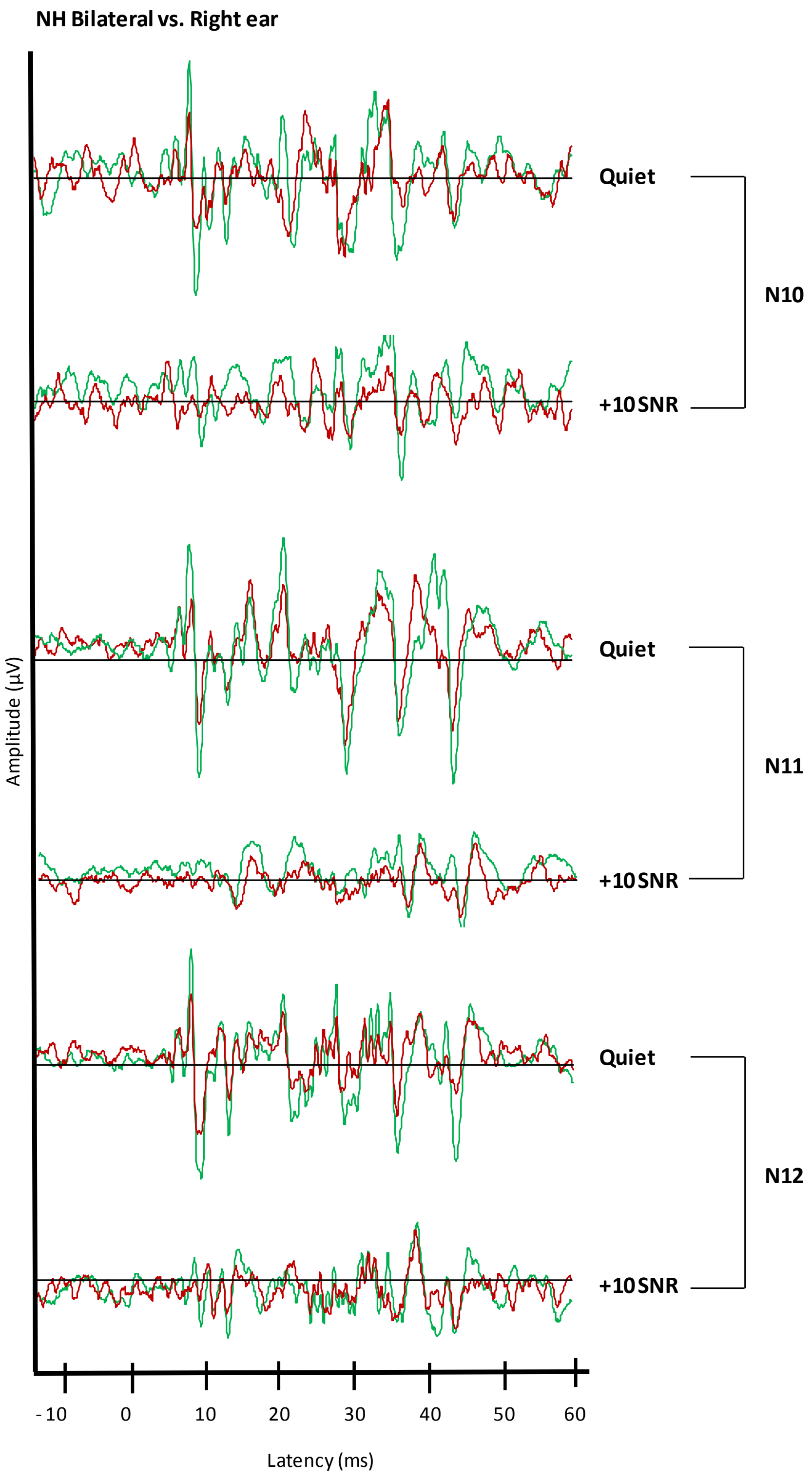


Figure 11. Average bilateral vs right ear stimulation for three NH participants for the quiet and +10 SNR conditions. Bilateral stimulation is in green, right ear stimulation is in red.

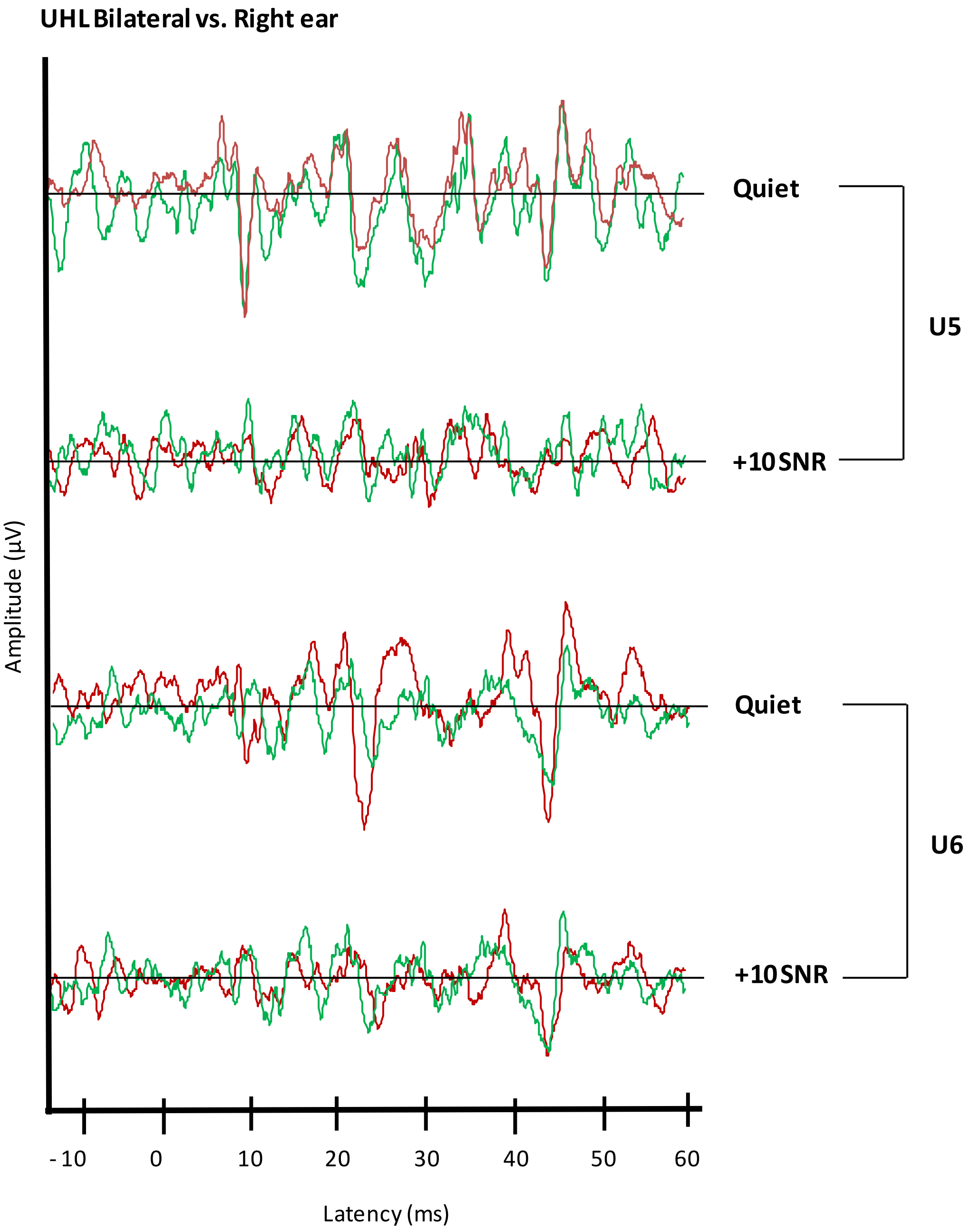


Figure 12. Average bilateral vs right ear stimulation for two UHL participants for the quiet and +10 SNR conditions. Bilateral stimulation is in green, right ear stimulation is in red.