Auditory Brainstem Response to Complex Sounds Predicts Self-Reported Speech-in-Noise Performance

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Abstract

Purpose—To compare the ability of the auditory brainstem response to complex sounds (cABR) to predict subjective ratings of speech understanding in noise on the Speech, Spatial, and Qualities of Hearing Scale (SSQ; Gatehouse & Noble, 2004) relative to the predictive ability of the Quick Speech-in-Noise test (QuickSIN; Killion, Niquette, Gudmundsen, Revit, & Banerjee, 2004) and pure-tone hearing thresholds.

Method—Participants included 111 middle- to older-age adults (range= 45–78) with audiometric configurations ranging from normal hearing levels to moderate sensorineural hearing loss. In addition to using audiometric testing, the authors also used such evaluation measures as the QuickSIN, the SSQ, and the cABR.

Results—Multiple linear regression analysis indicated that the inclusion of brainstem variables in a model with QuickSIN, hearing thresholds, and age accounted for 30% of the variance in the Speech subtest of the SSQ, compared with significantly less variance (19%) when brainstem variables were not included.

Conclusion—The authors' results demonstrate the cABR's efficacy for predicting self-reported speech-in-noise perception difficulties. The fact that the cABR predicts more variance in self-reported speech-in-noise (SIN) perception than either the QuickSIN or hearing thresholds indicates that the cABR provides additional insight into an individual's ability to hear in background noise. In addition, the findings underscore the link between the cABR and hearing in noise.

Keywords

central auditory processing; brainstem; speech-in-noise perception; clinical audiology; speech perception; electrophysiology; aging

Older adults often report difficulty hearing in background noise. Providing appropriate assessment and management for these individuals can be challenging for the audiologist and other clinicians. Historically, the traditional audiologic assessment included pure-tone threshold and word recognition measures; more challenging assessments, such as repeating sentences in competing background noise, were reserved for the assessment of central auditory processing. Researchers gave little thought to addressing the older adult's most

challenging concern—hearing speech in noise (SIN). The use of clinical measures of SIN perception, such as the Quick Speech-in-Noise test (QuickSIN; Killion, Niquette, Gudmundsen, Revit, & Banerjee, 2004), the Bamford-Kowal-Bench Speech-in-Noise test (BKB-SIN; Bench, Kowal, & Bamford, 1979), the Hearing in Noise Test (HINT; Nilsson, Soli, & Sullivan, 1994), and the Words-in-Noise test (WIN; Wilson, Abrams, & Pillion, 2003), has been more prevalent in the last decade. These measures classify performance into degrees of hearing handicap in noise, providing clinicians the information needed to make specific recommendations for hearing enhancement in noise (e.g., directional microphones, FM systems). Although these tests are useful, particularly when counseling patients, it remains challenging for clinicians to predict actual performance in difficult, real-world listening situations. Any assessment requiring a voluntary response is affected by cognitive factors, which can be compromised in the elderly (Dennis & Cabeza, 2007; Salthouse, 1985) —the group that most often seeks out assistance for hearing difficulties. What is needed, then, is an objective measure that is unaffected by cognitive status and can be used to predict real-world SIN performance.

An objective measure requires no response from the patient. Such measures, including auditory brainstem responses, otoacoustic emissions, and acoustic reflex thresholds, are routinely used for hearing screening and diagnosis in babies and other difficult-to-test patients (Hall, 2007). An objective measure for predicting SIN perception in the older adult population would require evaluation of more complex processing than that offered by simple stimulus detection and would be sensitive to age-related changes in central auditory system function. Researchers have documented the effects of aging on temporal resolution in the auditory system (Anderson, Parbery-Clark, White-Schwoch, & Kraus, 2012), which can generally be attributed to overall slowing of neural processing. This slowing may arise from a number of factors including, but not limited to, delayed neural recovery time (Walton, Barsz, & Wilson, 2008), decreased inhibition (Caspary, Ling, Turner, & Hughes, 2008), and increased temporal jitter (Pichora-Fuller, Schneider, MacDonald, Pass, & Brown, 2007). Evidence of neural slowing has been documented in the auditory cortex (Iragui, Kutas, Mitchiner, & Hillyard, 1993; Matilainen et al., 2010; Tremblay, Billings, & Rohila, 2004) and brainstem (Anderson, Parbery-Clark, Yi, & Kraus, 2011; Finlayson, 2002; Vander Werff & Burns, 2011). Neural slowing can affect precise encoding of temporal speech features, accounting in part for the older adult's difficulty with hearing in background noise (Tremblay, Piskosz, & Souza, 2002; Walton, 2010).

The auditory brainstem response to complex sounds (cABR) provides an objective means for evaluating the brainstem's ability to accurately encode timing and frequency information and also reflects neural slowing in older adults (Parbery-Clark, Anderson, Hittner, & Kraus, 2012; Vander Werff & Burns, 2011). The cABR's high reliability in individuals lends itself to clinical uses such as assessment and documentation of treatment outcomes (Hornickel, Knowles, & Kraus, 2012; Russo, Hornickel, Nicol, Zecker, & Kraus, 2010; Song, Nicol, & Kraus, 2011a, 2011b). The use of complex stimuli provides more sensitivity than do clicks or tone bursts to subtle differences in impaired populations, relative to normal controls (Song, Banai, Russo, & Kraus, 2006), thus highlighting the potential for the cABR to provide an effective means of assessing central auditory system function. In a previous study, we documented that accurate neural timing is an important factor in SIN performance in older adults (Anderson et al., 2011). In the present study, we examined the utility of the cABR for predicting self-reported SIN perception in older adults, using a clinically available software platform.

To achieve our objective of finding an efficacious measure of real-world performance, we compared the sensitivity of monaural, binaural, and binaural-in-noise presentation protocols for assessing differences in SIN perception. The monaural protocol has proved useful to

clinicians assessing language-based learning impairments in children (Banai et al., 2009), but we included the binaural protocol in case the monaural presentation failed to elicit a robust, replicable response in older adults. The binaural-in-noise presentation was used to simulate speech processing in degraded conditions. We did not include a monaural-in-noise protocol because pilot testing revealed that the individuals tested did not have a sufficiently replicable response for peak identification. Our aim was to determine which of these protocols was most predictive of self-reported SIN perception.

We also developed a stimulus-compensation protocol to reduce the effects of peripheral hearing loss on the cABR in individuals with hearing loss. This protocol created an amplified waveform based on individual hearing loss in each participant. We compared responses to these three presentation conditions using amplified and unamplified stimuli and anticipated that the use of amplified stimuli would minimize expected effects of audibility loss (e.g., loss of detectable response peaks) in individuals with a hearing loss.

We used the Speech, Spatial, and Qualities of Hearing Scale (SSQ; Gatehouse & Noble, 2004) because we wanted a measure that reflects self-reported performance rather than behavioral performance obtained in the clinic or laboratory. Specifically, by virtue of it being a self-report measure, the SSQ provides clinicians with important information about self-perception of the ability to perceive speech in noise, a common clinical complaint in older adults. The SSQ was developed in response to recognized limitations of the traditional audiological battery for predicting listening ability in challenging environments, such as rooms with multiple talkers and other noise sources. The SSQ covers a range of hearing contexts, asking individuals to rank perceived hearing difficulty ranging from easier one-on-one conversations in a quiet setting to conversing in a large, noisy restaurant. Gatehouse and Noble administered the SSQ to 153 patients with hearing loss prior to hearing aid fitting and concluded that the SSQ elicits new dimensions of hearing (e.g., attention switching, spatial hearing), thus providing a measure of complex and dynamic aspects of hearing in noise not captured by traditional assessment tools. Since its development, the SSQ has been used to document the benefit of using one versus two hearing aids (Most, Adi-Bensaid, Shpak, Sharkiya, & Luntz, 2012; Noble & Gatehouse, 2006), the advantages of directional microphones for speech intelligibility in noise (Wilson, McArdle, & Smith, 2007), and the benefit of cochlear implant algorithms (Vermeire, Kleine Punte, & Van de Heyning, 2010), as well as to obtain an individual self-assessment of speech understanding in noise abilities (Agus, Akeroyd, Noble, & Bhullar, 2009; Heifer & Vargo, 2009). The SSQ is a reliable instrument: Researchers administering tests 6 months apart (Singh & Pichora-Fuller, 2010) obtained test–retest correlations from both one-on-one interviews ($r = .83$) and mailed questionnaires ($r = .65$).

We predicted that the cABR, a highly reliable and objective measure of spectral and temporal resolution, would be a better predictor of real-world SIN performance than would clinical measures requiring patient responses. We expected that the effects of aging—including delayed neural recovery, decreased inhibition, and increased temporal jitter—would result in delayed onset and offset timing as well as decreased overall morphology and sharpness of the response to the stimulus onset.

Method

Participants

We recruited 111 participants (64 women, 47 men; ages 45–78; $M_{age} = 61.1$) from the Chicago area. We obtained audiometric thresholds at octave intervals (inter-octave at 3000 and 6000 Hz) from 125–12,000 Hz. The participants included individuals with hearing levels ranging from normal hearing to moderate hearing loss, with the exclusion of any

participant who had hearing thresholds greater than 40 dB HL (below 4000 Hz) or greater than 60 dB (from 4000 to 8000 Hz). Pure-tone averages (500–4000 Hz) ranged from 2.5 dB HL to 44.5 dB HL (M= 17.29, SD = 8.7; see Figure 1). In addition, no participant had air-bone gaps greater than 10 dB at 2 or more frequencies in either ear, nor had neurological disorders, asymmetric pure-tone thresholds (defined as > 15 dB difference at 2 or more frequencies between ears), delayed Wave V latencies for the click-evoked auditory brainstem response (defined as a latency > 6.8 ms at 80 dB SPL presented at a rate of 31.4 Hz), interaural Wave V latency differences greater than 0.2 ms, or nonreplicating onsets or offsets in the cABR. Finally, exclusionary criteria included IQ scores < 85 on the vocabulary and matrix design subtests of the Wechsler Abbreviated Scales of Intelligence (WASI; Zhu & Garcia, 1999) and scores < 22 (from participants who were age 60) on the Montreal Cognitive Assessment (MoCA; Nasreddine et al., 2005), a screening for cognitive impairment. Participants were compensated for their time and procedures were approved through the Northwestern University Institutional Review Board.

SIN

Self-Reported SIN Perception—Participants answered questions on the SSQ about hearing performance in various environments using a 10-point Likert scale, ranging from one-on-one listening in a quiet environment to listening to multiple talkers in a background of other talkers. In addition to measuring the ability to understand speech, the questionnaire also measures an individual's self-perception of localization abilities and judgment of sound quality. Because we are primarily interested in speech understanding, we restricted our analysis to the Speech subscale. We mailed the questionnaires to our participants and asked them to fill them out prior to coming to their appointments so that their answers would not be influenced by our testing. The Speech subscale has higher reliability (r = .83) than do the three combined subscales (r = .65) in mailed formats (Singh & Pichora-Fuller, 2010).

Clinical Measure of SIN Perception—We assessed SIN performance with the QuickSIN because of its widespread clinical use and its superior ability to separate performance between groups of participants with normal hearing and groups of participants with hearing impairment compared with other tests containing sentences, such as the BKB-SIN or HINT (Wilson et al., 2007). Four sets of six sentences were presented binaurally at 70 dB HL in a background of four-talker babble noise (three females and one male) through insert earphones (ER-2; Etymotic Research). The first set of sentences was presented at +25 dB signal-to-noise ratio (SNR), with the SNR decreasing by 5 dB for each subsequent sentence down to 0 dB SNR. Five key words in each sentence were marked as correct or incorrect. The total number of key words repeated correctly in each set of six sentences was subtracted from 25 to obtain the SNR loss in dB, defined as the difference between the individual's SIN threshold and the average SIN threshold (Killion et al., 2004). The SNR loss scores were averaged over the 4 lists to obtain the final SNR loss. A lower SNR loss score indicated better SIN performance.

Electrophysiology

Stimulus: The stimulus was a 40-ms [da] syllable synthesized in KLATT (Klatt, 1980). The stimulus began with a noise burst and was followed by a consonant-to-vowel transition. The fundamental frequency (F_0) of the stimulus rose linearly from 103 Hz to 125 Hz. The formant trajectories were as follows: The first formant rose from 220 Hz to 720 Hz, the second and third formants decreased from 1700 Hz to 1240 Hz and from 2580 Hz to 2500 Hz, respectively, and the fourth (3600 Hz) and fifth (4500 Hz) formants remained constant for the duration of the stimulus. The stimulus did not include the steady-state vowel of the syllable, but it was perceived as a consonant-vowel syllable. This stimulus has been used in previous studies examining rate (Krizman, Skoe, & Kraus, 2010), sex differences (Krizman,

Skoe, & Kraus, 2012), reading disorders (Banai et al., 2009), and maturation (Johnson, Nicol, Zecker, & Kraus, 2008). Figure 2 displays the stimulus and the grand average response.

An amplified stimulus was used for individuals who had hearing loss greater than 20 dB at any frequency from 125 Hz to 4000 Hz or greater than 25 dB at 6000 Hz or 8000 Hz. Using the National Acoustics Laboratory— Revised algorithm (NAL–R; Byrne & Dillon, 1986), we selectively amplified stimulus frequencies based on individual hearing thresholds in MATLAB (MathWorks).

For individuals with normal hearing, we presented the unamplified [da] stimulus at a rate of 10.9 Hz through electromagnetically shielded insert earphones (ER-3A; Natus Medical) at 80.3 dB SPL in the following three conditions: Monaurally (right ear) in quiet, binaurally in quiet, and binaurally in pink noise (+10 dB SNR). For participants with hearing loss, we presented both the amplified and the unamplified [da] stimuli for each of the three conditions (monaurally in quiet, binaurally in quiet, and binaurally in pink noise), making a total of six conditions. We chose the right ear for monaural presentation because right-ear stimulation produces more robust frequency encoding and earlier latencies than does stimulation to the left ear (Hornickel, Skoe, & Kraus, 2009). We presented the [da] stimuli in alternating polarities to minimize stimulus artifact and the cochlear microphonic (Gorga, Abbas, & Worthington, 1985; Russo, Nicol, Musacchia, & Kraus, 2004), an approach that emphasizes the envelope following response (Aiken & Picton, 2008; Campbell, Kerlin, Bishop, & Miller, 2012; Skoe & Kraus, 2010).

Recording: We recorded responses using the Biologic Navigator Pro System (Natus Medical). Prior to each recording, we calibrated the click and [da] stimuli to 80 dB SPL using a Brüel & Kjær 2238 Mediator sound level meter coupled to an insert earphone adapter. We sampled the SPL for each stimulus over 60 s to obtain the average SPL. Responses were recorded via a vertical electrode montage of four Ag-AgCl electrodes (central vertex [Cz] active, forehead ground, and linked earlobes reference) for the binaural recordings and three electrodes (same as described above, with only the right earlobe as reference) for the monaural recordings. We used a criterion of ± 23 μV for online artifact rejection. Two blocks of 3,000 artifact-free sweeps were collected in each condition for each participant and averaged using an 85.3-ms window, including a 15.8-ms prestimulus period. The responses were sampled at 12 kHz and were online bandpass-filtered from 100 Hz to 2000 Hz (12 dB/octave).

Data Analysis

We conducted data analysis using established MATLAB routines (Johnson et al., 2008; Krizman et al., 2010). A second observer manually identified and confirmed the onset peak and trough (labeled V and A) and the offset peak (labeled O; see Figure 2). Peaks that were not detectable were marked as missing data points and were excluded from the analysis. To obtain a measure of sharpness of the neural response, we calculated the slope between the onset peak (V) and trough (A). We also obtained a measure of the overall response morphology and neural fidelity to the stimulus by cross-correlating the stimulus and response waveforms, yielding a stimulus-to-response correlation value. These measures (onset latency and slope, offset latency, and response morphology) were obtained for all six conditions and were labeled as follows:

Monaural

Onset latency: V_{lat}

Onset slope: VA_{slope}

Offset latency: O_{lat}

Response morphology: STR_r

Binaural

Onset latency: Bi_V_{lat}

Offset slope: Bi_VA_{slope}

Offset latency: Bi_O_{lat}

Response morphology: Bi_STR_r

See Table 1 for means and standard deviations of all cABR variables for the monaural, binaural, and binaural-in-noise conditions.

Statistical Analysis

To determine the effectiveness of the amplification algorithm, we performed paired t tests between responses to amplified and unamplified stimuli for onset latency (V_{lat}), offset latency (O_{lat}), VA_{slope}, and morphology STR_r. We performed linear regressions, with the average SSQ score (14 items on the speech subscale) entered as the dependent variable and QuickSIN scores, pure-tone average (PTA; average of thresholds from 500–4000 Hz), Age, V_{lat}, O_{lat}, VA_{slope}, and STR_r entered in that order. Using the "Enter" method of multiple linear regression, we specified the order of variable entry to prevent brainstem variables from accounting for the variance that might have otherwise been ascribed to QuickSIN, PTA, and Age. We compared the outputs of the linear regressions for monaural versus binaural presentation conditions to determine the most efficacious protocol.

In all models, we checked residuals for normality to ensure that the linear regression analysis was appropriate for the data set (Kolmogorov-Smirnov Test; $M = 0$, $SD = 0.97$, $p = .355$). We ran collinearity diagnostics with satisfactory variance inflation factor (highest = 2.02) and tolerance (lowest = 0.494) scores, indicating the absence of strong correlations between two or more predictors.

Results

Amplification Algorithm

Monaural presentation—We applied the amplification algorithm in the 50 of 111 cases in which hearing loss exceeded our criteria for normal thresholds. Stimulus amplification in the monaural presentation resulted in greater onset and offset peak detectability (amplified: 47 of 50 detectable onsets and 44 of 50 detectable offsets vs. unamplified: 38 of 50 detectable onsets and 35 of 50 detectable offsets; Related-Samples McNemar Test: VA_{slope}, $p = .031$; O_{lat}, $p = .004$). Comparisons of responses to the unamplified versus amplified stimuli in individuals with hearing loss revealed that VA_{slope} was sharper in the amplified versus unamplified stimuli, $t(37) = 2.887$, $p = .0006$: $M_{amplified} = -0.29$, $M_{unamplified} = -0.25$. Although O_{lat} was slightly earlier for the amplified stimuli, the differences were not significant, $t(34) = 0.384$, $p = .703$: $M_{amplified} = 48.83$ ms, $M_{unamplified} = 48.91$ ms. The STR_r values did not differ between conditions, although the r value was slightly higher in the amplified condition, $t(49) = 0.837$, $p = .437$: $M_{amplified} = 0.113$, $M_{unamplified} = 0.106$. The final number of participants with hearing loss with detectable onsets and offsets was 44. The final total of participants (those with normal hearing and those who were hearing impaired) with detectable onsets and onsets was 104. All individuals with normal hearing had detectable onsets and offsets. Figure 3 compares the average waveforms of participants with hearing loss in response to amplified versus unamplified stimuli.

Binaural presentation—The response to the binaural presentation was robust, with detectable onset peaks in all responses to amplified or unamplified stimuli and little difference in detectability of the offset peaks (amplified: 48 of 50 detectable offsets vs. unamplified: 44 of 50 detectable offsets; Related-Samples McNemar Test: O_{lat}, $p = .219$). The greatest effects were seen for the onset, with Bi_V_{lat} earlier and Bi_VA_{slope} sharper in responses to amplified versus unamplified stimuli—Bi_V_{lat}, $t(49) = 3.662$, $p = .001$; $M_{amplified} = 6.62$ ms, $M_{unamplified} = 6.74$ ms; Bi_VA_{slope}, $t(49) = 5.250$, $p < .001$, $M_{amplified} = -0.45$, $M_{unamplified} = -0.37$. The Bi_O_{lat} and Bi_STR_r values did not differ significantly between conditions: Bi_O_{lat}, $t(43) = 1.213$, $p = .234$, $M_{amplified} = 49.17$ ms, $M_{unamplified} = 49.35$ ms; Bi_STR_r: $t(49) = 0.529$, $p = 600$, $M_{unamplified} = 0.093$, $M_{unamplified} = 0.097$. All individuals with normal hearing had detectable onsets and offsets.

Binaural-in-noise presentation—The response to the binaural-in-noise presentation was degraded compared with the responses in binaural quiet and monaural presentations. We found little difference between responses to amplified or unamplified stimuli with equivalent detectability of the onset peaks (36 of 50 detectable onsets to both amplified and unamplified stimuli) and offset peaks (amplified: 36 of 50 detectable offsets vs. unamplified: 39 of 50 detectable offsets; Related-Samples McNemar Test: Bin_O_{lat}, $p = 1.00$). There were no significant differences between amplified and unamplified measures ($Bin\_V_{lat:}$ $p > .1$; Bin_VA_{slope}, Bin_O_{lat}, and Bin_STR_r: $p > .5$). We also observed a loss of replicability in the responses of individuals with normal hearing ($N = 60$; 47 of 60 and 51 of 60 detectable onsets and offsets, respectively).

Multiple Linear Regression

Monaural presentation—Results of multiple linear regression analysis indicated that our selected brainstem variables predicted a greater amount of variance in self-assessed SIN perception on the SSQ in middle- to older-age adults than did PTA, QuickSIN, and Age. We chose to use the "Enter" method of linear regression, which specifies the order of variables entered into the model. By entering the cABR variables last, we ensured that the cABR variables did not use up the variance that might have otherwise been attributed to PTA, QuickSIN, or Age. Our model (PTA, QuickSIN, Age, V_{lat}, O_{lat}, VA_{slope}, and STR_r, entered in this order) is a good fit for the data, $F(6,103) = 5.982$, $p < .001$, with an R^2 value of .306. Only the brainstem variables of O_{lat} and STR_r significantly contributed to the variance. Table 2 provides standardized (β) and unstandardized (B) coefficients and levels of significance for the independent variables. In order to disambiguate the contributions of brainstem variables from other measures, we reran the regression hierarchically with PTA, QuickSIN, and Age on the first step and brainstem variables on the second step. The variables on the first step contributed significantly to the variance in SSQ, $F(2, 103) = 5.721$, $p = .001$, with an R^2 value of .148. The addition of brainstem variables in Step 2 produced a significant change to the variance, R^2 change = .158, $F(3, 103) = 5.413$, $p = .001$. Table 3 provides standardized coefficients (β), changes in R^2, and levels of significance for the variables in Models 1 and 2.

Binaural presentation—Results using the binaural presentation indicated again that selected brainstem variables predicted a greater amount of variance in self-assessed SIN perception on the SSQ than did PTA, QuickSIN, and Age. Our model ("Enter" method: PTA, QuickSIN, Age, Bi_V_{lat}, Bi_O_{lat}, Bi_VA_{slope}, and Bi_STR_r, entered in this order) is a satisfactory fit for the data, $F(6,103) = 2.608$, $p = .017$, with an R^2 value of .170. Only the Bi_STR_r significantly contributed to the variance of the model. Table 4 provides standardized (β) and unstandardized (B) coefficients and levels of significance for the independent variables. We reran the regression hierarchically with PTA, QuickSIN, and Age on the first step and brainstem variables on the second step. Again, the variables on the first

step contributed significantly to the variance in SSQ, $F(2,103) = 5.721$, $p = .001$, with an R^2 value of .148. However, we found that the addition of brainstem variables in Step 2 did not produce a significant change to the variance, R^2 change = .073, $F(3, 103) = 1.964$, $p = .107$. Table 5 provides standardized coefficients (β), changes in R^2, and levels of significance for the variables in Models 1 and 2.

Binaural-in-noise presentation—The lack of detectable peaks in individuals with either normal hearing or hearing loss resulted in a total number of 56 of 111 participants who had both detectable onsets and onsets, because some of the participants who had detectable onsets did not have detectable offsets and vice versa. Results of the linear regression indicated that the model including PTA, QuickSIN, Age, Bin_V_{lat}, Bin_O_{lat}, Bin_VA_{slope}, and Bin_STR_r variables was not satisfactory for predicting SSQ, $F(6, 55) = 1.778$, $p = .117$, $R^2 = .224$. The results of the binaural-in-noise presentation should be interpreted with caution, however as we did not have the recommended number of participants for performing a linear regression analysis (98; see Green, 1991).

Correlations—Tables 6 and 7 display intercorrelations among the SSQ and the independent variables—monaural cABR variables in Table 6 and binaural cABR variables in Table 7. The following variables were related to SSQ: PTA, QuickSIN, Age, monaural onset latency (O_{lat}), and monaural and binaural morphology (STR_r and Bi_STR_r). No significant correlations were noted between the SSQ and the binaural-in-noise cABR variables. Scatter plots demonstrating relationships among SSQ and O_{lat} (monaural presentation), QuickSIN, and PTA are presented in Figure 4.

Summary—Brainstem variables (particularly the offset latency and stimulus-to-response correlation) significantly contribute to the variance in self-perception of SIN ability; in fact, they contribute greater variance than either hearing thresholds or QuickSIN scores. The monaural presentation protocol predicted greater variance than did the binaural protocol (Hotelling's t/Stegler's Z: $t_{103} = 2.05$, $Z = 2.00$, $p < .05$). In individuals with hearing loss, the use of amplified stimuli produced more detectable peaks, sharper onset slopes, and greater overall morphology (stimulus-to-response correlations) than did the use of unamplified stimuli.

Discussion

Our results demonstrate the important role of subcortical function in SIN performance as perceived by the listener. In our model, offset latency and overall morphology of the response waveform made significant contributions to the predictions of self-assessed SIN ability. Our study also revealed that using an amplified stimulus for the cABR produced more replicable waveforms in individuals with hearing loss, thereby reducing the number of participants who needed to be excluded from the analysis. The monaural protocol was most efficacious for predicting SIN perception, likely because ceiling effects in the binaural-in-quiet presentation produced robust responses in almost all participants, limiting its ability to differentiate between good and poor SIN perceivers. On the other hand, floor-like effects were apparent in the binaural-in-noise presentation in which the noise degraded the neural responses in many participants to such a degree that useful information from the response was limited.

What are the mechanisms underlying the offset latency's importance for successful communication in background noise? Detection of stimulus offsets and onsets contributes to the activation of duration-tuned neurons in the inferior colliculus and at higher levels of the auditory system (Brand, Urban, & Grothe, 2000; Faure, Fremouw, Casseday, & Covey, 2003). Researchers have posited that duration selectivity results from temporal interaction of

excitatory and inhibitory inputs that are offset in time (for review, see Sayegh, Aubie, & Faure, 2011). Activation of inhibitory transmitters is essential for duration tuning; for example, when pharmacological inhibitory antagonists are applied, duration tuning is abolished (Casseday, Ehrlich, & Covey, 2000). Caspary et al. (2008) documented the reduction of inhibitory transmitters in the midbrains of older mammals. Taken together, these results suggest that imprecise duration tuning is one of the consequences of aging; in fact, deficits in duration discrimination for tones and gaps in noise have been observed in older versus younger adults (Fitzgibbons & Gordon-Salant, 1994). In addition, duration-tuned neurons are tuned in frequency and amplitude, so that responses of these neurons are highly specific. Therefore, duration-tuned neurons may act as spectrotemporal filters (Sayegh et al., 2011), providing the precise encoding necessary for understanding speech in noise.

The other brainstem factors contributing to variance in SIN perception—reduced onset slope and poorer stimulus-to-response correlation (representing decreased morphology)—can result from temporal jitter or loss of neural synchrony that accompanies aging. The SIN performance of young adults with normal hearing when they listen to temporally jittered speech decreases to the levels expected of older adults (Pichora-Fuller et al., 2007), providing a potential explanation for the older adults' listening-in-noise difficulties. We did not, however, find the expected relationships between age and onset latency (O_{lat}), onset slope (VA_{slope}), and morphology (STR_r). The lack of relationship between these variables and age might be explained by the restricted age range in our study, which did not include anyone younger than 45 years. Because onset latencies can be delayed in adults as young as 47 years (Parbery-Clark et al., 2012), the relationship between age and latency might have been obscured by an age-related delay in all of our participants.

Even though the QuickSIN's contribution to the SSQ variance was less than that of the cABR, the QuickSIN and other clinical tests of SIN perception remain an important part of the audiological protocol. In the first author's experience, patients often express satisfaction that their actual difficulty has finally been evaluated after being tested with the QuickSIN. We are not recommending that these tests be dropped from the protocol; rather, we suggest that clinicians be aware of the limitations of a strictly behavioral protocol. Cognitive factors, such as memory or attention, will affect tests results, such as those of the QuickSIN (Parbery-Clark, Skoe, Lam, & Kraus, 2009; Shinn-Cunningham & Best, 2008), and memory and/or attention may be compromised in some older adults (Pichora-Fuller, 2003). Therefore, the clinician should consider the QuickSIN and other SIN test results in the context of the patient's overall function and his or her stated difficulties.

If one accepts that an objective measure of SIN perception is warranted in the assessment of older adults, how can the cABR be incorporated into clinical practice? The protocol for obtaining the measures described in this article requires approximately 20 min (including time for electrode application). While we acknowledge that a typical audiologist cannot routinely extend the assessment time by 20 min, the cABR nevertheless can be considered for inclusion when an individual's reports of hearing difficulty are not reflected in the traditional battery of speech and pure-tone tests. In Figure 5 we provide two examples of cABRs from participants who have good and poor SSQ scores, respectively. While the individual with a better SSQ score has poorer hearing thresholds and QuickSIN score, he has earlier onset and offset latencies, a sharper slope, and better cABR morphology. We envision the use of such measures as informing the clinician of the need to assess suprathreshold auditory function; in the future, a clinician might rely on normative values to assess auditory function in an individual patient. For example, the cABR may benefit patients who are having inordinate difficulties adjusting to their hearing aids, thus helping clinicians determine whether problems with central auditory processing are interfering with

patients' ability to benefit from amplification and whether auditory training or assistive listening devices are indicated (for review, see Anderson & Kraus, in press). Because the cABR is highly reliable and consistent over time (Song et al., 2011b), its uses are interpretable on an individual level, suggesting a use for monitoring changes. The cABR has been used to document training benefits in children (Russo, Nicol, Zecker, Hayes, & Kraus, 2005) and young adults (Song, Skoe, Banai, & Kraus, 2012), but more work is needed to determine the cABR's efficacy for predicting and assessing training benefit in older adults.

We chose to use the SSQ rather than a more direct measure of SIN perception, such as the QuickSIN, because we wanted to address individual self-perception of ability, which is what generally motivates someone to seek help for hearing difficulties. In addition, the SSQ is an approximation of overall, day-to-day SIN performance, as opposed to a one-time test in a clinic. The linear regression model used in this study predicted 30% of the variance in the SSQ, leaving much of the variance attributed to unknown factors. Personality characteristics and occupations likely affect individual answers on the SSQ. The person who works in a noisy area with high communication demands will answer questions differently than would the older, retired individual who spends much of his or her time at home watching television. If we had selected a standardized clinical or laboratory SIN perception measure as our predicted variable, we expect that our model might have predicted more variance because the dependent variable would be somewhat freer of the influence of personality and lifestyle biases. It should be noted that our data set is not typical for patients of an audiologic clinic, in that most of them came to our laboratory to participate in research, not because they were seeking treatment or advice for hearing problems. Nevertheless, many of our participants were motivated to participate in the study because they had noticed some trouble when listening in noise and wanted to participate in a research study before seeking clinical consultation. In the future, we plan to extend this analysis to a clinical population of individuals seeking treatment for hearing loss.

Other factors, such as cortical processing, cognitive function, aging, and general life experiences, would also add to the predicted variance of our model. The auditory cortex can make use of degraded or limited signals and translate them into meaningful input, as is noted in individuals with auditory neuropathy (Kraus et al., 2000) or those who wear cochlear implants (Psarros et al., 2009). Therefore, cortical processing likely contributes significantly to SIN perception. Although age did not significantly contribute to the variance in the SSQ in our data set, it has been established that age-related declines in cognitive function affect clinical and laboratory measures of SIN perception (Gordon-Salant & Fitzgibbons, 1997; Humes, 2007; Pichora-Fuller & Souza, 2003). The ability to compensate for loss of acoustic or linguistic redundancy in unfavorable environments is compromised by age-related decreases in prefrontal lobe function, thus affecting memory, attention, and inhibition of unwanted background noise (Wong, Ettlinger, Sheppard, Gunasekera, & Dhar, 2010). These changes affect performance on clinical measures of SIN perception; for example, working memory is related to QuickSIN scores in both young (Parbery-Clark et al., 2009) and older (Parbery-Clark, Strait, Anderson, Hittner, & Kraus, 2011) adults with normal hearing.

Even though SIN perception difficulties are frequently found in older adults, age did not significantly contribute to our model. Deficits in SIN perception are present as early as middle age (ages 45–54; Heifer & Vargo, 2009); therefore, in our data set, self-perception of speech in noise in all of our participants may have been affected by aging to some extent. Finally, life experiences, such as years of musical training, offset age-related declines in SIN perception (Parbery-Clark et al., 2011). Therefore, a comprehensive model must necessarily include cortical, cognitive, and life experiences in addition to the subcortical and peripheral measures used in this study. Our future work will evaluate interactions among peripheral,

central (brainstem and cortical), cognitive, and life-experience variables using structural equation modeling.

Conclusion

The cABR provides an objective means for assessing the central processes contributing to SIN perception. Our results demonstrate evidence in the cABR of a possible link between neural slowing, as evidenced by delayed offset, reduced morphology, and diminished SIN perception. In the future, this objective test may play a role in the audiological protocol, particularly in patients whose reported hearing difficulties, whether aided or unaided, are greater than would be predicted from traditional audiological measures; therefore, the clinical use of the cABR merits further study. Our analysis also contributes to the understanding of the biological mechanisms underlying SIN perception.

Acknowledgments

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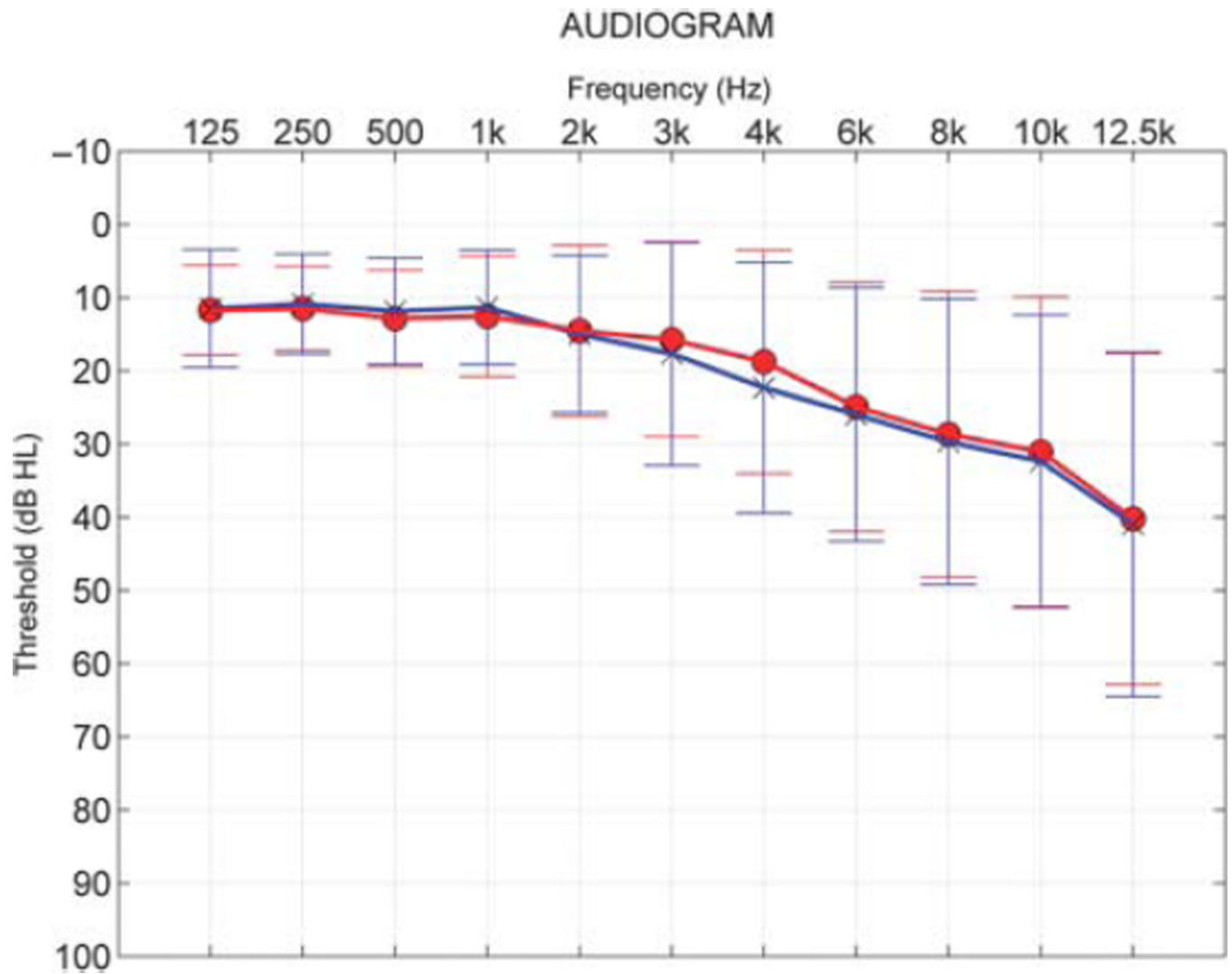
AUDIOGRAM

Figure 1.
Means are displayed for the right (red) and left (blue) ear audiometric thresholds for all participants ($N = 104$). Error bars = 1 *SD*.
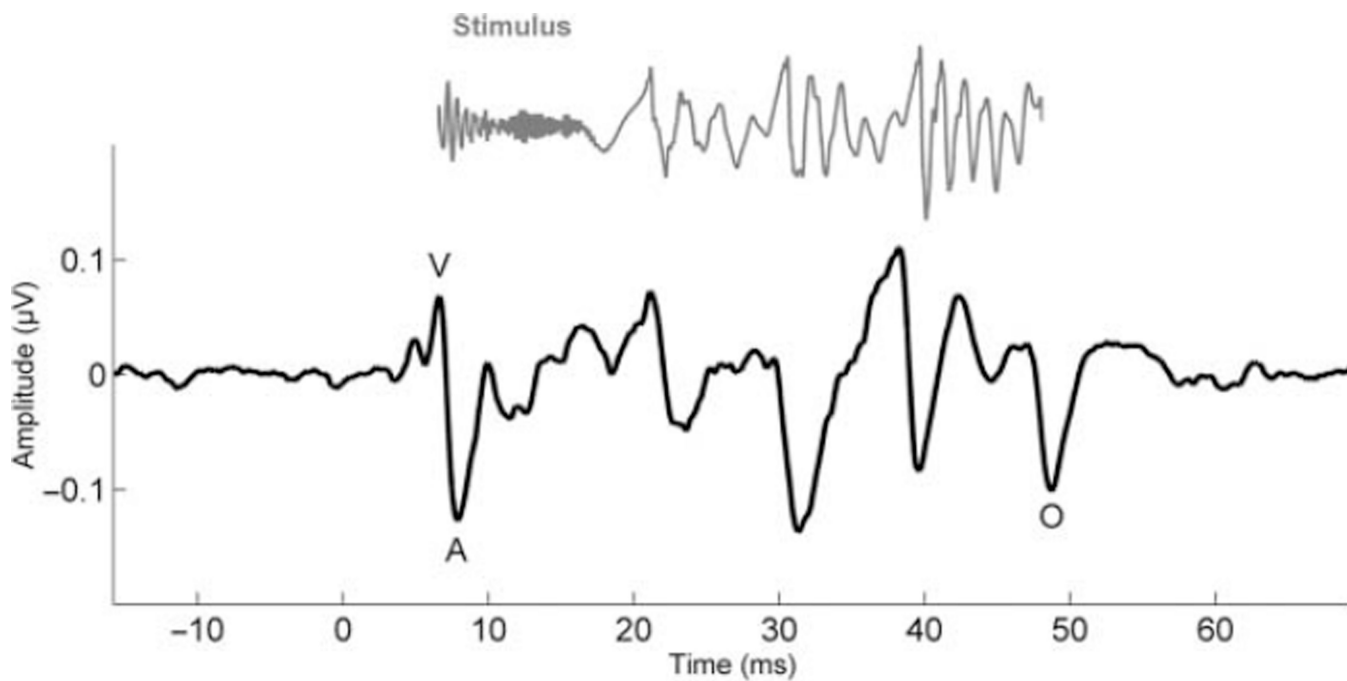
Figure 2.
The 40-ms stimulus (gray) compared with the grand average response to the monaural presentation of the speech syllable [da] in 61 participants with normal hearing (black). The stimulus was temporally shifted to account for neural lag and to allow visual comparison between the stimulus and the response. The onset peaks are labeled V and A, and the offset peak is labeled O.
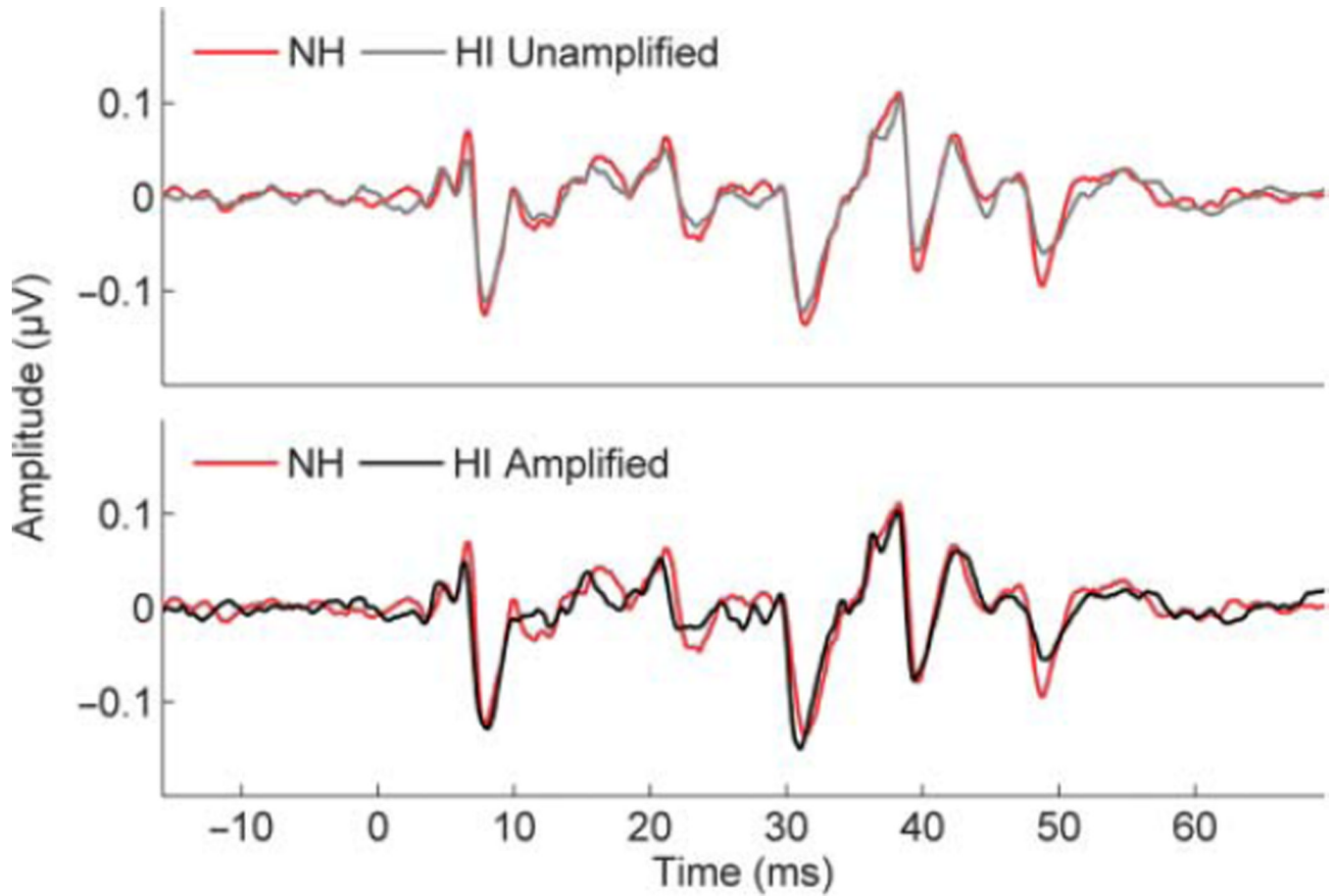
Figure 3.
Top panel: Grand average responses for 61 normal-hearing (NH) individuals (red) and 51 hearing impaired (HI) individuals (gray) to the unamplified [da] stimulus presented monaurally. Bottom panel: Same as for top panel, except that responses of the HI (black) are recorded to a [da] stimulus that has been created for each individual's hearing loss based on the National Acoustics Laboratory—Revised (NAL-R) algorithm. The amplification algorithm serves to lessen the effects of reduced audibility on responses of participants who are hearing impaired, especially for the response onset (VA).

Figure 4.
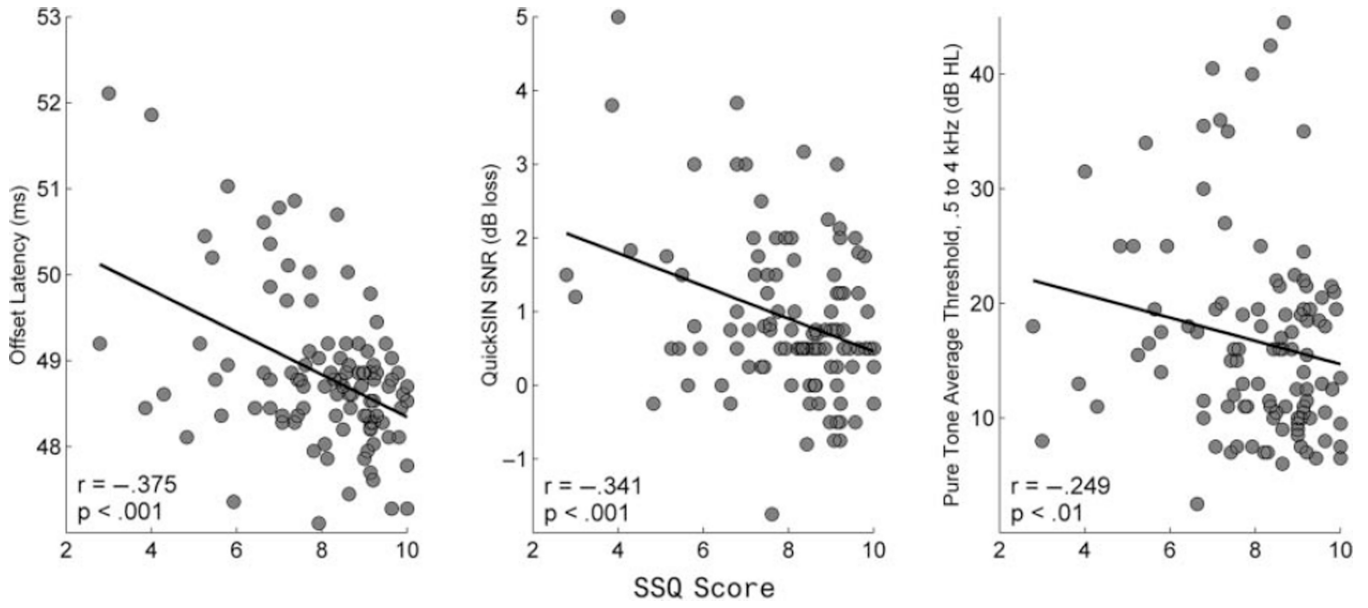Scatter plots demonstrating the relationships among the subjective ratings of speech-in-noise (SIN) performance (Speech subscale of Speech, Spatial, and Qualities of Hearing Scale [SSQ]), offset latency, and clinical measure of SIN ability and hearing thresholds. QuickSIN = Quick Speech-in-Noise test; SNR = signal-to-noise ratio.
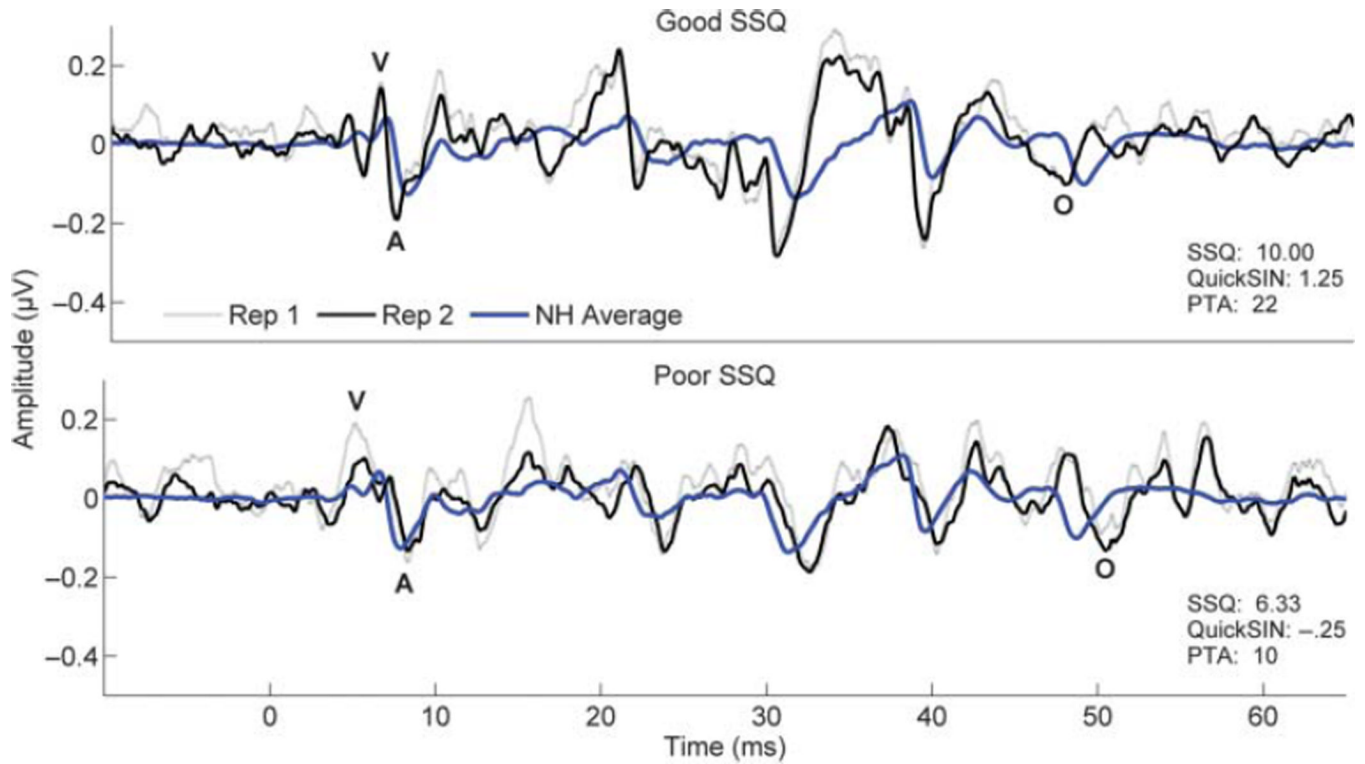
Figure 5.
Examples of individual waveforms in response to the monaural presentation in participants who have good (left) or poor (right) SSQ scores. Two responses to the stimulus (gray and black) for each participant are overlain to demonstrate replicability. The average response from the normal-hearing group (blue) is also overlain. In spite of the participant's hearing loss, the good SSQ example (left) shows larger, sharper responses than is observed for the normal-hearing participant with a relatively poorer SSQ score (right). PTA = pure-tone average.

Table 1

cABR variables in the monaural and binaural protocols ($N = 104$) and the binaural-in-noise protocol ($N = 56$).

Variable	M	SD
V_{onstel}	6.75	0.34
O_{lat}	48.78	0.83
VA_{slope}	−0.28	0.11
STR_r	0.10	0.05
Bi_V_{onset}	6.72	0.33
Bi_O_{lat}	49.03	0.86
B_VA_{slope}	−0.44	0.17
Bi_STR_r	0.09	0.05
Bin_V_{onset}	7.37	0.67
Bin_O_{lat}	49.38	0.79
Bin_VA_{slope}	−0.17	0.08
Bin_STR_r	0.13	0.06

Note. These values are calculated from responses of normal-hearing participants to unamplified stimuli and from responses of hearing impaired participants to amplified stimuli. Effects of noise include delayed latencies and shallower slopes. cABR = auditory brainstem response to complex sounds.

Table 2

Summary of "Enter" hierarchical regression analysis for variables predicting self-assessment of speech-in-noise (SIN) ability ($N=104$).

Variable	B	SE B	β	p
PTA[a]	−0.001	0.020	−.172	.994
QuickSIN[a]	0.024	0.174	.016	.891
Age	−0.040	0.024	−.172	.094
V_{onset}	0.245	0.566	.053	.666
O_{lat}[b]	−0.799	0.228	−.416	.001
VA_{slope}	2.830	1.633	.186	.086
STR_r[b]	−7.602	2.648	−.259	.005

Note. Unstandardized (*B* and *SE B*) and standardized (β) coefficients in a model of contributions from an audiological protocol and the cABR to variance in the average Speech, Spatial, and Qualities of Hearing Scale (SSQ) score.

[a]Measures from the typical audiological protocol (pure-tone average [PTA] and Quick Speech-in-Noise test [QuickSIN]) do not significantly predict variance in SSQ.

[b]In this model, only the contributions of two brainstem variables (O_{lat} and STR_r) to SSQ are significant.

Table 3

Summary of "Enter" two-step hierarchical regression analysis for variables predicting self-assessment of SIN ability ($N = 104$).

Variable	ΔR^2	β	p
Model 1	.148		.001
PTA		−.101	.365
QuickSIN		−.207	.063
Age		−.170	.119
Model 2	.158		.001
PTA		−.008	.994
QuickSIN		.016	.891
Age		−.172	.094
V_{lat}		.053	.666
O_{lat}		−.416	.001
VA_{slope}		.186	.086
STR_r		−.259	.005

Note. Standardized (β) coefficients in models comparing separate contributions (ΔR) from the audiological protocol and the cABR to the SSQ score. The contributions of both models are significant predictors of the SSQ. However, only the cABR variables (O_{lat} and STR_r) predict significant individual variance to the SSQ.

Table 4

Summary of "Enter" hierarchical regression analysis for variables (binaural presentation) predicting self-assessment of SIN ability (N= 104).

Variable	B	$SE\ B$	β	p
PTA	−0.009	0.021	−.052	.661
QuickSIN	−0.322	0.193	−201	.099
Age	−0.035	0.026	−.148	.185
Bi_V$_{onset}$	−0.350	0.637	−.073	.584
Bi_O$_{lat}$	0.320	0.217	.174	.144
Bi_VA$_{slope}$	−0.611	1.188	−.065	.608
Bi_STR$_r$	−7.331	2.989	−.258	.016

Note. Unstandardized (B and $SE\ B$) and standardized (β) coefficients and p values. Although the overall model significantly predicts the SSQ, F(6, 103) = 2.61, p = .017, only the contribution of one cABR variable (Bi_ STR$_r$) is significant.

Table 5

Summary of "Enter" two-step hierarchical regression analysis for variables (including binaural cABR variables) predicting self-assessment of SIN ability ($N = 104$).

Variable	ΔR^2	β	p
Model 1	.148		.001
PTA		−.101	.365
QuickSIN		−.207	.063
Age		−.170	.119
Model 2	.105		.107
PTA		−.052	.661
QuickSIN		−.201	.099
Age		−.148	.185
Bi_V$_{lat}$		−.073	.584
Bi_O$_{lat}$		−.416	.001
Bi_VA$_{slope}$		.174	.144
Bi_STR$_r$		−.258	.016

Note. Standardized (β) coefficients in models comparing separate contributions from the audiological protocol and the cABR (binaural) to the SSQ score. The contribution of the first model (audiological protocol only) significantly predicts variance in the SSQ, but the cABR (binaural) variables do not significantly add to the predictive power of the model. Nevertheless, only the Bi_STR$_r$ variable predicts significant individual variance to the SSQ.

Table 6

Intercorrelations between SSQ and the independent variables, including the monaural cABR variables.

Variables	1	2	3	4	5	6	7	8
1. SSQ								
2. PTA	−.249 **							
3. QuickSIN	−.341 **	.474 **						
4. AGE	−.293 **	.445 **	.428 **					
5. V_{lat}	−.005	−.142	−.023	.054				
6. O_{lat}	−.375 **	.294 **	.474 **	.346 **	.458 ***			
7. VA_{slope}	.115	−.010	−.135	.090	.569 ***	.458 ***		
8. STR_r	−.222 *	.270 **	.146	.043	−.178	−.025	−.049	

Note. Results of Pearson's correlational analyses indicated that SSQ, PTA, and QuickSIN are all related to the offset latency (O_{lat}) in the monaural cABR. Neither onset latency (V_{lat}) nor slope (VA_{slope}) is related to SSQ, PTA, QuickSIN, or Age. The morphology of the response (STR_r) is weakly related to SSQ and PTA.

*
$p < .05$.

**
$p < .01$.

***
$p < .001$.

Table 7

Intercorrelations among SSQ and the independent variables, including the binaural brainstem variables.

Variables	1	2	3	4	5	6	7	8
1. SSQ								
2. PTA	−.249 *							
3. QuickSIN	−.341 ***	.474 ***						
4. Age	−.293 **	.445 ***	.428 ***					
5. Bi_V$_{lat}$	−.018	−.151	−.068	.041				
6. Bi_O$_{lat}$	−.067	.156	.364 ***	.195	.349 ***			
7. Bi_VAslope	−.053	.014	−.056	.054	.631 ***	.296 **		
8. Bi_STR$_r$	−.280 **	.234 *	.185	.062	.035	.319 **	.141	

Note. Results of Pearson's correlational analysis indicated that SSQ is most strongly related to QuickSIN and age. It is weakly related to PTA and morphology (Bi_STR$_r$). QuickSIN, PTA, and Age are moderately correlated with each other. QuickSIN is also related to the offset latency (Bi_O$_{lat}$).

*
$p < .05$.

**
$p < .01$.

***
$p < .001$.