10-1-2011

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Benjamin W. Y. Hornsby
Vanderbilt University

Earl E. Johnson
East Tennessee State University, johnsoe@etsu.edu

Erin Picou
Vanderbilt University

Citation Information

Hornsby, Benjamin W. Y.; Johnson, Earl E; and Picou, Erin. 2011. Effects of Degree and Configuration of Hearing Loss on the Contribution of High- and Low-Frequency Speech Information to Bilateral Speech Understanding. *Ear and Hearing*. Vol.32(5). 543-543. https://doi.org/10.1097/AUD.0b013e31820e5028
ISSN: 0196-0202

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Published in final edited form as:
Ear Hear. 2011 ; 32(5): 543–555. doi:10.1097/AUD.0b013e31820e5028.

Effects of degree and configuration of hearing loss on the contribution of high- and low-frequency speech information to bilateral speech understanding

Benjamin W. Y. Hornsby, Ph.D.[a], **Earl E. Johnson, Ph.D.**[b], and **Erin Picou, Au.D.**[a]

[a]Vanderbilt University, Department of Hearing and Speech Science, Dan Maddox Hearing Aid Research Laboratory, Vanderbilt Bill Wilkerson Center, Room 8310 Medical Center East, South Tower, 1215 21st Ave. South, Nashville, TN 37232-8242

[b]U.S.A. Department of Veterans Affairs & East Tennessee State University, Department of Communicative Disorders, PO Box 4000, Audiology-126, Mountain Home, TN 37684

Abstract

Objectives—The purpose of this study was to examine the effects of degree and configuration of hearing loss on the use of, and benefit from, information in amplified high- and low-frequency speech presented in background noise.

Design—Sixty-two adults with a wide range of high- and low-frequency sensorineural hearing loss (5–115+ dB HL) participated. To examine the contribution of speech information in different frequency regions, speech understanding in noise was assessed in multiple low- and high-pass filter conditions, as well as a band-pass (713–3534 Hz) and wideband (143–8976 Hz) condition. To increase audibility over a wide frequency range, speech and noise were amplified based on each individual's hearing loss. A stepwise multiple linear regression approach was used to examine the contribution of several factors to 1) absolute performance in each filter condition and 2) the change in performance with the addition of amplified high- and low-frequency speech components.

Results—Results from the regression analysis showed that degree of hearing loss was the strongest predictor of *absolute* performance for low- and high-pass filtered speech materials. In addition, configuration of hearing loss affected both *absolute* performance for severely low-pass filtered speech and *benefit* from extending high-frequency (3534–8976 Hz) bandwidth. Specifically, individuals with steeply sloping high-frequency losses made better use of low-pass filtered speech information than individuals with similar low-frequency thresholds but *less* high-frequency loss. In contrast, given similar high-frequency thresholds, individuals with flat hearing losses received more benefit from extending high-frequency bandwidth than individuals with more sloping losses.

Conclusions—Consistent with previous work, benefit from speech information in a given frequency region generally decreases as degree of hearing loss in that frequency region increases. However, given a similar degree of loss, the configuration of hearing loss also affects the ability to use speech information in different frequency regions. Except for individuals with steeply sloping

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Address correspondence to: Benjamin W. Y. Hornsby, Vanderbilt Bill Wilkerson Center, Room 8310 Medical Center East, South Tower, 1215 21st Ave. South, Nashville, TN 37232-8242, 615-936-5132 (p) / 615-936-6914 (f), ben.hornsby@vanderbilt.edu.

high-frequency losses, providing high-frequency amplification (3534–8976 Hz) had either a beneficial effect on, or did not significantly degrade, speech understanding. These findings highlight the importance of extended high-frequency amplification for listeners with a wide range of high-frequency hearing losses, when seeking to maximize intelligibility.

I. INTRODUCTION

A common strategy for addressing the communication difficulties of persons with hearing loss is to provide hearing aids. A primary goal of the fitting is to restore audibility to portions of speech which, due to the hearing loss, would otherwise be inaudible. This rehabilitative strategy is based on the assumption that restoring audibility will help reduce communication difficulties. However, some research suggests that persons with sensorineural (SNHL) are limited in their ability to make use of information in amplified speech, particularly the amplified high-frequency components of speech (Ching et al., 1998; Turner and Cummings 1999; Hogan and Turner, 1998; Vickers et al., 2001; Baer et al., 2002; Amos and Humes, 2007). Several studies have suggested that this limited benefit is related to the degree of high-frequency hearing loss. Specifically, when degree of high-frequency (≥3000–4000 Hz) hearing loss exceeds 55–80 dB HL, benefit from amplification of speech components within this high-frequency region is limited (Hogan and Turner, 1998; Ching et al., 2001). Amos and Humes (2007) found that elderly listeners, regardless of their degree of high-frequency hearing loss, were unable to benefit from information provided by amplified speech components as bandwidth increased from 3200 to 6400 Hz. These studies suggest that the utility of information from amplified high-frequency (≥3000 Hz) speech components may be reduced for persons with any degree of high-frequency SNHL, but particularly when thresholds exceed 55–80 dB HL. In contrast, for lesser degrees of hearing loss, or for hearing losses in lower frequency regions, improving audibility via amplification generally improves speech understanding (e.g., Ching et al., 1998; Hornsby and Ricketts, 2003).

A factor which may complicate the interpretation of some of the results described above is configuration of hearing loss. Much of the research showing limited benefit from high-frequency information is based on results from individuals with sloping high-frequency hearing loss. The presence of moderate-to-severe SNHL, regardless of the frequency, often results in poorer than predicted speech understanding (e.g., Pavlovic 1984; Ching et al., 1998). Thus, if study participants have sloping high-frequency SNHL, poorer utility of high-frequency, compared to low-frequency, speech information would be expected. This makes it difficult to separate the degradation in understanding due to hearing loss in general from degradation due to hearing loss at high frequencies.

One way to avoid the confound of variation in hearing loss with frequency is to examine performance in persons with flat hearing losses. Hornsby and Ricketts (2003) used this approach to attempt to disentangle the effects of frequency region of hearing loss and degree of hearing loss on benefit from high-frequency speech information. They used filtered speech-in-noise testing to determine the filter cutoff frequency at which scores for low- and high-pass filtered speech were the same (the crossover frequency). The crossover frequency essentially divides the wideband speech spectrum into two equally important halves. Crossover frequencies were used to examine the impact of hearing loss on the utility of high- and low-frequency speech information for persons with moderate-to-severe flat SNHL (high-frequency thresholds between 60–80 dB HL). The results showed poorer-than-normal speech recognition for individuals with flat SNHL in all filter conditions; however, crossover frequencies were not significantly different from those of normal-hearing participants. This suggests that, given a similar degree of loss across frequency, the impact of hearing loss on the utility of speech information is similar in the low- and high-frequency regions.

In a follow up study using the same paradigm, Hornsby and Ricketts (2006) compared their past results from individuals with flat losses to results from participants with sloping high-frequency losses. Participants from the two studies had similar high-frequency thresholds (60–80 dB HL) but very different low-frequency thresholds. Consistent with several previous studies, the participants with sloping losses received less benefit from amplified high-frequency speech components than a normal-hearing control group. However, the limited utility of amplified high-frequency speech components was similar for the flat and sloping groups. The primary difference between groups was in the utility of information provided by the amplified *low-frequency* speech components. Participants with high-frequency sloping losses showed reduced utility of high-frequency speech information and near-normal utility of low-frequency information, where their thresholds were better. In contrast, those with flat hearing losses showed reduced utility of speech information uniformly across the entire frequency range. These findings are consistent, in part, with previous work showing that SNHL degrades speech understanding in noise and that the degradation may increase with increases in threshold. In contrast to previous work, however, results from Hornsby and Ricketts suggested that, given similar amounts of hearing loss, the ability to extract information from amplified speech components is similar at the high and low frequencies.

The review above highlights the somewhat conflicting findings regarding the benefits provided by amplification of the high-frequency components of speech. The reasons for the conflicting findings are not entirely clear but may be related to differences across studies in degree and configuration of hearing loss, type of speech material, presence of background noise, type of frequency shaping and presence of cochlear dead regions. For example, Turner and Henry (2002) highlighted the impact of background noise on the utility of information within amplified high-frequency speech components. They essentially replicated the study of Hogan and Turner (1998) but tested speech understanding in noise rather than quiet. In contrast to results obtained in quiet, all participants received benefit from high-frequency information (>3000 Hz), regardless of their degree of hearing loss. However, thresholds at 3000 and 4000 Hz for most participants in this study were generally 70 dB HL or better.

Several investigators have shown that listening to speech at higher-than-normal levels can reduce performance (Studebaker et al. 1999; Dubno et al. 2005a,b; Hornsby et al. 2005). To achieve adequate audibility, individuals with moderate or greater hearing loss are forced to listen to speech at these higher levels. Hornsby and Ricketts (2006) used the Speech Intelligibility Index (SII: ANSI S3.5, 1997) to demonstrate that simply amplifying speech to levels commonly presented through hearing aids can significantly reduce the utility of high-frequency speech information. In an attempt to equate listening conditions across participants, several studies have used “generic” amplification methods that present speech at levels substantially higher than would have been provided by a well fitted hearing aid, at least for participants with less severe losses (e.g., Ching et al., 1998; Hogan and Turner 1998; Amos and Humes, 2007).

Horwitz et al. (2008) provided empirical evidence that this over-amplification could significantly affect benefit from high-frequency information. They found that understanding improved significantly with the addition of high-frequencies (4500–5600 Hz) when amplification was individualized based on the degree of hearing loss. In contrast, when a “generic” amplification scheme that provided the same high-frequency amplification for all subjects regardless of their degree of hearing loss was used, performance did not improve with the addition of high-frequency information. In addition, more individuals showed a decrease in performance with the increase in high-frequency bandwidth when the generic scheme was used. Compared to the individualized method, amplified speech levels were substantially higher for several subjects using this generic scheme. These data are consistent with past research showing that attempting to maximize high-frequency audibility in the presence of severe hearing loss can result in speech levels in the high-frequency regions that degrade, rather than improve, performance (e.g., Rankovic 1991; Hornsby and Ricketts 2006).

Another factor that may play a role in the divergent findings across studies is the presence or absence of cochlear dead regions. The term “dead region” is used to suggest a “complete loss of inner hair cells (IHCs) over a certain region of the basilar membrane” and/or the fact that “afferent auditory neurons innervating those places may be non-functioning” (Moore et al. 2000, p. 205). Even with sufficient amplification to allow detection of speech, improved understanding is only expected if the information in the newly audible speech can be accurately transmitted to higher auditory areas. This may not be possible in the presence of cochlear dead regions (Vickers et al., 2001; Baer et al., 2002).

Currently, the presence of a dead region within the cochlea can only be definitively confirmed post mortem. However, performance on behavioral masking tests, such as the Threshold Equalizing Noise (TEN) test and psychoacoustic tuning curves (PTCs), can provide strong evidence for the presence of a dead region (see Moore, 2004 for a review). The probability of a positive finding using the TEN test (suggesting a cochlear dead region) generally increases with increasing hearing loss (Vinay and Moore, 2007). This has led some researchers to suggest that the limited benefit of high-frequency information for individuals with more severe hearing loss observed in some studies was due, in part, to the presence of high-frequency dead regions in those subjects.

Finally, the majority of studies in this area have assessed performance monaurally, essentially eliminating potential benefits from binaural listening and spatial separation of the speech and noise. This is clearly not representative of typical listening conditions nor is it optimal in terms of maximizing understanding. One recent study reported a small but significant benefit in aided speech intelligibility when extending high-frequency bandwidth but only when the speech and maskers were spatially separated (Moore et al., 2010). Thus, the limited benefit provided by amplified high-frequency speech seen in some studies may actually underestimate the potential benefit in more realistic settings (e.g., binaural listening in the presence of multiple, spatially separated, noise sources).

The review above suggests that several factors may influence the utility of amplified high-frequency speech information. As technological developments make it possible to provide usable gain at higher and higher frequencies, improving our understanding of the benefits, and limitations, of amplification at high frequencies becomes even more important. In this study we examine the effects of configuration of hearing loss on the utility of information in amplified high- and low-frequency speech components. The speech is presented bilaterally in the presence of multiple, spatially separated, uncorrelated noises and amplified using individualized, clinically appropriate, amplification scheme. A large number of participants were chosen to provide a wide range of hearing loss slopes and degree of high-frequency hearing loss.

II. MATERIALS AND METHODS

A. Participants

Participants were seventy-four adults, 12 with normal hearing (NH; 4 male, 8 female) and 62 with hearing loss (37 male, 25 female). All participants with NH passed a pure-tone air conduction screening at 20 dB HL (250–8000 Hz; ANSI 1996) and had no history of otologic pathology. NH participants ranged in age from 22 to 40 years (mean: 26 years). Participants with hearing loss had symmetric SNHL (air-bone gaps ≤ 10 dB). The hearing loss was considered symmetric if the difference between ears met all of the following requirements 1) ≤20 dB difference at any single frequency, 2) ≤15 dB difference at any two adjacent frequencies and 3) < 10 dB difference for the pure tone average (PTA) at 500, 1000 and 2000 Hz. Participants with hearing impairment (HI) ranged in age from 49 to 88 years (mean: 71 years). All HI participants completed the Short Portable Mental Status Questionnaire (SPMSQ; Pfeiffer 1975) to rule out significant cognitive dysfunction. Their median score was 0 (no errors) and ranged from 0–2. Scores >5 are suggestive of moderate or greater intellectual impairment. Hearing aid use data were inadvertently not collected for 4 participants; the majority of remaining participants (~87%) were existing hearing aid wearers and approximately 80% of these wore bilateral hearing aids. The median duration of hearing aid use was 2 years (range 1 month-35 years).

HI participants were chosen to include a wide range of high-frequency SNHLs. Auditory thresholds were assessed, using ER3A insert earphones, at octave frequencies between 250–8000 Hz and at 1500, 3000 and 6000 Hz. Thresholds ranged from 5–115 dB HL. In a few cases where there was no measurable response, for the purposes of averaging, threshold was assumed to be 5 dB greater than the maximum output of the audiometer. This occurred primarily at 8000 Hz (18 of 124 ears) and at 6000 Hz for a single participant.

Participants had configurations ranging from relatively flat across a wide frequency range to steeply sloping in the high frequencies. We characterized configuration of loss by calculating a difference between high- and low-frequency thresholds, averaged across ears. For convenience we refer to this difference as a “bilateral slope”. To calculate the bilateral slope, thresholds at each frequency were first averaged across ears. Slopes were then calculated by subtracting the bilateral high-frequency average (HFA; average at 3, 4 and 6 kHz) from the bilateral low-frequency average (LFA; average at 250, 500 and 1000 Hz). The median bilateral slope was 34.2 dB and slopes ranged from −9.2 dB to 65.8 dB. When characterized in terms of change in threshold per octave, slopes ranged from −25 to 70 dB per octave. Figure 1 shows the distributions of low- and high-frequency average thresholds (Top Panel) and slope values (Bottom Panel) for the HI participants.

B. Procedures

Sentence recognition in noise was assessed for various high- and low-pass filter cutoff frequencies. The speech and noise were presented bilaterally and the noise was on continuously during the speech testing. Filter cutoff frequencies were chosen to coincide with edge frequencies associated with the 1/3rd octave band center frequencies used in the ANSI S3.5 (1997) method for calculating the Speech Intelligibility Index (SII). Speech recognition was assessed in the following ten filter conditions for all test participants: low-pass 1403, 1795, 2244 and 3534 Hz; high-pass 1426, 1114, 713 and 357 Hz; wideband (143–8976 Hz), and band-pass (713–3534 Hz). In addition, cochlear function in the HI participants was assessed using the SPL version of the Threshold Equalizing Noise (TEN SPL) test (Moore et al. 2000). Details regarding the procedures and outcomes from the TEN test are provided in Hornsby and Dundas (2009). Study procedures were reviewed and approved by the Vanderbilt Institutional Review Board in compliance with the Office of

Human Resource Protection requirements. All participants provided informed consent prior to initiating any study procedures and were compensated for their time on a per session basis.

1. Sentence recognition testing

a. Speech materials: Sentence recognition was assessed using a modified version of the Connected Speech Test (CST; Cox et al. 1987, 1988). The modifications are related to the background noise and are described later. The CST uses everyday connected speech as the test material and consists of 28 pairs of passages (24 test and 4 practice pairs). Each pair of passages contains 50 key words for scoring purposes. Two passage pairs were completed in each filter condition, and the score for each condition was based on the average for these two passage pairs. In isolated cases (11 total), if the researcher felt that performance in a given filter condition was particularly variable (e.g., scores differed by 20 percentage points) and time allowed, a third passage pair was presented and the score was based on the average of all three passage pairs. All speech testing was completed in one or two test sessions with at least one CST passage pair used for each filter condition during each session. The order of filter conditions was randomized across participants.

Digital copies of CST passages were obtained from the original laser disk recording of the audio-visual materials (Cox et al. 1987) and stored on a computer hard drive via an IEEE 1394 Firewire digital video bridge. The audio sampling rate was 44.1 kHz. To allow time for participant response between sentences, audio files were edited to insert approximately 5 seconds of silence between each sentence. Only the audio portions of these stimuli were used in the current study.

b. Speech and noise recording process: To provide appropriate amplification without feedback, the speech and noise were recorded through both ears of a KEMAR manikin positioned in the center of an anechoic chamber (6.7 (length) × 4.7 (width) × 6.4 (height) meters). To ensure that the high-frequency components of CST speech were above the noise floor, prior to recording through KEMAR a high-frequency pre-emphasis was applied to all speech stimuli. However, no such pre-emphasis was applied to the noise stimuli. This type of difference in speech and background noise spectra occurs in real-life situations (i.e., speech and noise are rarely spectrally matched). However, in comparison to a condition where the speech and noise are spectrally matched, the better SNR at high-frequencies in this study likely improved the utility of these high-frequencies. The pre-emphasis was applied using the FFT filter function in Adobe Audition (Version 1.5). A fixed FFT filter using a 2048 FFT size and Blackman window was created to apply 10 dB of gain to the high-frequency components above 1700 Hz. A linear transition (on a log frequency scale) was used to apply 0 to 10 dB gain to frequency components between 440–1700 Hz. No gain was applied to frequencies below 440 Hz.

The speech and noise materials were presented from Tannoy 600 loudspeakers located 1.25 meters from KEMAR. The speech loudspeaker was located at 0° azimuth and the noise loudspeakers were positioned evenly (72° increments) around the KEMAR (36°, 108°, 180°, 252°, and 324°). The background noise consisted of five, 90 second, uncorrelated segments of steady noise that were spectrally shaped to match the long term spectrum of the CST keywords. Both ears of KEMAR were fitted with Zwislocki couplers paired to Etymotic Research ER11 ½" microphones. The microphone outputs were amplified and recorded (44.1 kHz sampling rate) through an Audigy 2 ZS external sound card and saved as a stereo file using CoolEdit Pro™ Version 1.1. A speech calibration noise was created by applying the same high-frequency pre-emphasis as used on the CST speech materials to a steady state noise, spectrally matched to the 1/3rd octave long term rms levels of the original CST passages. This calibration noise was presented from the speech loud speaker, recorded through KEMAR and used for later shaping and calibration purposes. Figure 2 shows the 1/3rd octave band levels, at KEMARs ears, of our speech calibration noise and background noise. The data in Figure 2 represent levels prior to hearing-loss-specific frequency shaping. The recorded stimuli were further shaped on an individual basis, as described below, and presented bilaterally using Etymotic Research ER-5A™ insert earphones. These earphones approximate the TDH-39 earphone response at the eardrum while providing a higher maximum output than ER3A™ insert earphones.

c. Selection of signal-to-noise ratio for testing: To limit floor and ceiling effects, the SNR for each HI participant was chosen such that, if possible, performance in the widest bandwidth condition was near 80% and performance in the narrowest bandwidths was not at floor level. Although this was not always possible, mean performance was approximately 79% in the wideband condition and approximately 22% in both the narrowest low- (1403 Hz) and high- (1426 Hz) pass conditions. The median SNR, based on wideband overall rms levels, for HI participants was +7 dB and ranged from −2 to +20 dB. A limit of +20 dB was used to ensure that background noise levels were greater than circuit noise across at all test frequencies.

d. Frequency shaping: Linear frequency shaping was provided to both the speech and noise to compensate for each individual’s hearing loss. Real ear target output levels were derived for each participant based on modifications to the Desired Sensation Level (DSL 4.1; Cornelisse et al. 1995) prescriptive formula. Modifications included 1) a 3 dB level reduction due to binaural presentation and 2) assuming a 65, rather than 70 dB SPL, speech level. These modifications resulted in an overall reduction in prescribed real ear levels of 8 dB, relative to DSL 4.1 targets. These modified levels offered a compromise between maximizing audibility and maintaining acceptable loudness.

Stereo files containing speech stimuli recorded from KEMARs left and right ears were output from a computer at a fixed level and routed to separate inputs of a TDT SM3 mixer. The recorded background noise was output from a separate computer, attenuated to achieve the desired SNR and mixed with the speech using the TDT SM3 mixer. The mixed speech and noise signals were routed to a two-channel custom built software program (using Tucker Davis Technologies Real-Time Processor Visual Design Studio (RPvdsEX) and an RX8 multiprocessor array) designed to apply ear and frequency-specific linear gain based on each individual’s hearing loss. The program did not provide any compression or output limiting. Speech peak amplitudes were monitored on an oscilloscope prior to testing to ensure that speech stimuli were not clipped during processing. All participants listened to practice passages prior to testing to ensure that levels were not uncomfortably loud. The shaped and amplified signals were then low- or high-pass filtered (using an 800th order, linear phase, FIR filter) based on the desired test condition. Filter coefficients were derived using Matlab’s FIR1 function and implemented in the RPvdsEX software. These filters provide a fixed attenuation slope in dB/Hz beyond the filter cutoff frequency. Therefore, slope in dB/octave varied with cutoff frequency (e.g., approximately 10 dB/octave for the low-frequency edge in the high-pass 400 Hz condition and over 600 dB/octave for the high-frequency edge in the wideband (143–8976 Hz) condition).

Gain values for each ear were adjusted manually to achieve the desired real ear output levels. In a few cases, gain values were slightly reduced from target due to complaints of loudness. Match-to-targets for wideband speech were verified for each individual by measuring the 1/3rd-octave rms levels of the calibration noise (recorded through KEMAR), presented via ER5 insert earphones, in a Zwislocki coupler using a Larson-Davis 814 sound level meter (slow averaging, flat-weighting). The custom software program provided a good deal of flexibility allowing for a close match to target. Median deviations from target were <

1 dB across the frequency range of 250–6000 Hz. Over 93% of measured values were within ±5 dB of target and 99% were within ±10 dB. This procedure did not precisely replicate presentation of free field stimuli through bilateral hearing aids. However, it did ensure that participants received appropriate, ear-specific spectral shaping and gain based on their degree of hearing loss. Figure 3 shows the range of deviations from real ear targets based on 1116 measures (9 frequencies × 2 ears × 62 participants).

2. Speech intelligibility index (SII) calculations—Despite the provision of hearing loss specific amplification, speech audibility varied across participants. Factors such as SNR differences between listeners, equipment output limitations coupled with the magnitude of some hearing losses, and loudness tolerance all affected speech and noise levels and thus audibility across listeners. To quantify audibility across conditions and for each participant, 1/3rd octave band SII calculations (ANSI S3.5, 1997) were used to generate SIIs for each filter condition.

Monaural thresholds (in dB HL) obtained in quiet, were interpolated or extrapolated to match the 1/3rd octave center frequencies used in the SII calculations and adjusted to account for binaural listening using correction factors (1.5- 3.8 dB) suggested by Pavlovic (1987). Thresholds were obtained using a standard clinical method (i.e., down 10 dB, up 5 dB). These thresholds, along with levels of the speech and noise, were used to determine the proportion of audible speech information in each 1/3 octave frequency band. Speech levels at each ear, after shaping based on the individual hearing loss was applied, were estimated by measuring the level of our speech calibration noise, output through the ER5A insert earphones, in a Zwislocki coupler. According to Sherbecoe and Studebaker (2003), the calibration noise, which was based on entire CST passages, is 1 dB weaker than the CST key words used for scoring. Therefore, in the SII calculations 1 dB was added to the 1/3rd octave band speech levels measured in the Zwislocki coupler. One-third octave band background noise levels for each ear were also measured in a Zwislocki coupler for each participant. The background noise was the same 90-second recording of the 5 source uncorrelated noises used during speech testing and was presented at the same level the participants listened to during their testing.

To calculate SII values, the ANSI S3.5 (1997) protocol requires the use of free field speech and noise levels. Therefore, 1/3rd octave band speech and noise levels measured in a Zwislocki coupler (i.e., simulated real ear levels) were converted to free field levels using the average free-field to eardrum transfer function provided in the ANSI S3.5 (1997) standard. Effective speech peak levels specific to the CST (Sherbecoe and Studebaker, 2002), rather than the 15 dB peaks as in the ANSI standard, were used in the SII calculations. In addition, the frequency importance function specifically derived for the CST materials was used to weight the audible information in each frequency band (Sherbecoe and Studebaker 2002). ANSI S3.5 corrections for high presentation levels and spread of masking effects were included in the calculations. However, no corrections for hearing loss desensitization were utilized. Following the method used by Humes (2002), the better ear SII value at each 1/3rd octave frequency was used to calculate a bilateral SII.

To use the SII to predict performance in a given condition, a transfer function relating the SII to percent correct performance is required. Sherbecoe and Studebaker (2002) generated a transfer function for the CST materials based on normal hearing listeners' performance in multiple, monaural listening conditions. These authors, however, calculated an articulation index (AI) using methods that were somewhat different than those in the ANSI S3.5 (1997) standard and different from those used in the current study. Humes (2002) found that, when using a modification of the ANSI S3.5 (1997) standard to calculate SIIs, a variation of the transfer function proposed by Sherbecoe and Studebaker provided a better fit to wideband

CST performance measured at various SNRs. Using the SII calculation method described above and data from our NH participants in multiple filter conditions, we compared the predictive accuracy of the two transfer functions. Speech recognition for the NH participants was assessed using speech and noise that were spectrally shaped as if for a person with hearing loss. Specifically, the speech and noise were shaped to approximate DSL targets for a person with a flat 65 dB HL, or a gently sloping (250–4000 Hz thresholds of 35–70 dB HL), hearing loss. However, overall levels for the NH participants were adjusted to limit loudness discomfort. Average CST performance plotted as a function of SII for each filter condition is shown in Figure 4 along with the transfer functions proposed by Sherbecoe and Studebaker (2002) and Humes (2002). Given our method of calculating the SII, the function proposed by Humes (2002) provided a better match (rms error: 12.6 versus 13.8 percentage points) to our data and was therefore used in this study.

III. RESULTS

A. Sentence recognition

Figure 5 shows individual, and average, measured and SII predicted scores as a function of low and high-pass filter condition for the HI participants. On average, measured performance was poorer than predicted across all filter conditions. Differences between predicted and measured performance as a function of filter condition were examined using a repeated-measures analysis of variance (ANOVA). Due to violation of the ANOVA assumption of sphericity, a Greenhouse-Geisser correction was used when determining significance of test results. Prior to statistical analyses all speech scores were converted to rationalized arcsine units (rau) to stabilize error variance (Studebaker 1985). The within-subjects independent variables were score type (SII predicted and behaviorally measured) and filter cutoff frequency. The dependent variable was the CST score in each filter condition. Speech understanding scores in the low- and high-pass conditions were evaluated separately; wideband scores were included in both analyses.

Low-pass filter conditions—The ANOVA for the low-pass conditions revealed significant main effects of score type ($F_{1,61} = 25.98$, $p < 0.001$) and low-pass filter cutoff frequency ($F_{4,244} = 754.8$, $p < 0.001$). Predicted scores were significantly higher than measured scores and scores increased as the filter cutoff increased. Follow up testing comparing measured and predicted scores in each filter condition was conducted using a series of single factor ANOVAs. In total, 10 planned comparisons were completed, four low-pass, four high-pass, wideband, and bandpass (LP713–3534 Hz) conditions. The level of significance for each ANOVA ($p = 0.005$) was based on a Bonferonni correction ($p = 0.05/10$) to control for the increased likelihood of type-1 error due to multiple comparisons. Results showed that, except for the LP1403 Hz condition ($p = 0.114$), measured scores were significantly lower than predicted ($p < 0.005$).

There was a significant interaction between score type and filter cutoff frequency ($F_{4,244} = 23.6$, $p < 0.001$). As can be seen in Figure 5 (top panel), differences between measured and predicted scores increased systematically as the low-pass filter cutoff frequency increased, from about 5 rau in the LP1403 Hz condition to about 22 rau in the wideband condition.

High-pass filter conditions—The ANOVA on the high-pass and wideband filter conditions revealed significant main effects of score type ($F_{1,61} = 111.5$, $p < 0.001$) and filter cutoff frequency ($F_{4,244} = 1016.1$, $p < 0.001$). Predicted scores were higher than measured scores and performance increased as the high-pass filter cutoff frequency was lowered. Follow up testing using a series of single factor ANOVAs showed that measured performance was lower than predicted ($p < 0.005$) in all filter conditions.

There was a significant interaction between score type and filter cutoff frequency ($F_{4,244}$ = 20.3, $p < 0.001$). However, in contrast to the low-pass data, differences between predicted and measured scores decreased as low-frequency components were added (i.e., as high-pass filter cutoff frequency was lowered). The largest difference (35.7 rau) was observed in the narrowest (HP1426 Hz) filter condition and it systematically decreased to about 22 rau in the wideband condition.

B. Factors affecting performance in various filter conditions

Consistent with previous research, measured scores were, on average, lower than predicted based on audibility (adjusted based on SII corrections for spread of masking and high presentation levels). A stepwise multiple linear regression approach was used to determine the contribution of various factors to measured performance in each filter condition. The variable accounting for the most variance was entered into the regression equation first. The remaining variables were then evaluated and the variable accounting for most of the remaining variance, if it significantly reduced the variance of the model predictions ($p < 0.05$), was entered into the equation. This process continued until all variables were entered or excluded from the model. If none of the variables significantly reduced the variance of the model predictions then none were entered.

TEN test results were not included in this analysis because for many of our participants it was difficult to determine if a “continuous” dead region (i.e., positive findings at multiple adjacent frequencies) was present and, if present, the location of the edge frequency (fe) of the dead region. In the current study, participants with positive TEN results at multiple adjacent frequencies were rare (see Hornsby and Dundas, 2009 for details). In many cases participants had positive findings at a few adjacent frequencies but these were often bounded by inconclusive or, in some cases, negative findings or the pattern of TEN results varied between ears. Inconclusive results were common (~25% of thresholds tested) with almost 80% of the ears having at least one inconclusive result. Inconclusive results were due primarily to the severity of hearing loss at high frequencies coupled with an inability, due to loudness tolerance issues, to present the TEN at a high enough level to achieve the required masking needed to determine the presence or absence of a dead region. In addition, procedural factors such as the use of a 5 dB step size during the TEN testing also likely affected the number of inconclusive results observed.

These ambiguities made it difficult to confirm fe for many of our participants. Clear delineation of fe is needed because work by Moore and colleagues suggests that fe dictates the optimal amplification bandwidth for persons with high and low frequency dead regions. Specifically high-frequency amplification beyond 1.7*fe or low frequency amplification below 0.57*fe for individuals with high and low- frequency dead regions, respectively, may not be beneficial and in some cases may degrade performance (Vickers et al., 2001, Vinay and Moore, 2007b). Without the presence of a clear fe it was not possible to statistically compare benefit from amplification above 1.7*fe (or below 0.57*fe) for individuals with and without dead regions. Because of this inability we chose to exclude TEN findings from the regression analysis.

Factors included as predictor variables in the stepwise multiple linear regression analyses were SII predicted scores (a measure of audibility), degree of low (LFA) and high (HFA) frequency hearing loss, and age. The dependent variables were the measured CST score (in rau) in each filter condition. A direct measure of audiogram slope was not included as a predictor variable due to the strong correlations between degree of high- and low-frequency loss and slope. However, inclusion of both low- and high-frequency thresholds allowed us to assess the contribution of slope. Inclusion of SII predicted scores accounted for differences in audibility between participants due to differences in individual thresholds and test SNRs.

We chose to use the SII predicted score as a measure of audibility, rather than the absolute SII value, to capture situations where equivalent changes in SII result in substantial differences in changes in predicted score. For example, assuming the CST transfer function used in this study, a 0.2 change in SII results in a change in predicted score of about 68% when the absolute SII increases from 0.2 to 0.4. In contrast, the same 0.2 change in SII results in a change in predicted score of less than 1% when the absolute SII increases from 0.8 to 1.0. Inclusion of thresholds as a predictor variable provides a measure that may be associated with changes in suprathreshold processing abilities due to differences in cochlear damage (i.e., possible reductions in spectral and temporal processing abilities associated with hearing loss).

In a multiple regression analysis, strong correlations between predictor variables are problematic. If present, small changes in data values may lead to large changes in regression coefficients making the regression model estimates unreliable. Table 1 shows the Pearson's correlation values between predictor variables used in the regression analysis. Several significant correlations were observed. However, these relationships were generally weak suggesting a minimal effect of multicollinearity on the regression analyses. The strongest correlation ($r = 0.354$; $r^2 = 0.125$) was between bilateral high-frequency average thresholds and LP1403 Hz predicted scores.

Results of these analyses are shown in Table 2. The results suggest that the relative contribution of audibility (SII predicted scores), degree of low- and high-frequency hearing loss and age to aided speech understanding in noise varied across filter conditions. The regression models accounted for a minimum of approximately 22% (BP713–3534 Hz) to a maximum of 44% (HP1426 Hz) of variance in measured speech scores. In general, degree of hearing loss was the strongest predictor of measured performance (except for the LP1403 Hz condition). In all low-pass filter conditions, and the wideband and band-pass conditions, degree of low-frequency hearing loss entered into the regression equation first, or second in one case. In addition, coefficient values were always negative suggesting that as degree of low-frequency hearing loss increased, speech understanding decreased. Likewise, for all high-pass filter conditions, degree of high-frequency hearing loss accounted for the most variance. Again coefficient values were always negative suggesting that, as degree of high frequency hearing loss increased, speech understanding decreased.

The SII predicted scores were not, in general, a strong predictor of measured performance in any one filter condition. In the LP1403 Hz condition, the SII predicted score entered first into the regression equation and accounted for approximately 11% of the variance. However, in four other conditions SII predicted scores were the second or third variable to enter into the regression equation and accounted for only an additional 4%-7% of the variance. SII predicted scores did not enter into the model at all in five of the 10 test conditions. Likewise, age was not a strong predictor of performance, accounting for only 5%-6% of the variance in two filter conditions. In both of these conditions coefficients were negative suggesting that as age increased performance decreased (Table 2).

When degree of hearing loss was entered into the regression model, coefficients were generally negative, suggesting that as thresholds increased speech understanding decreased. However, in conditions where understanding was based primarily on very low-frequency information (LP1403 and LP1795 Hz), both low- and high-frequency thresholds entered into the regression model. As expected, coefficients for low-frequency thresholds were negative, consistent with poorer performance as low-frequency thresholds worsened. In contrast, coefficients for high-frequency thresholds were positive suggesting that measured performance in these conditions actually improved as high frequency thresholds worsened (Table 2). The contrasting effects of degree of high- and low-frequency hearing loss suggest that audiogram slope plays an important role in the understanding of low-pass filtered speech. Specifically, given similar low-frequency thresholds, individuals with steeply sloping audiograms (more high-frequency hearing loss) may better utilize low-frequency speech information than individuals with shallower sloping or flat losses.

To confirm the contribution of audiogram slope to speech understanding, regression analyses were repeated including slope of hearing loss as a variable instead of degree of low- and high-frequency hearing loss. Age and SII predicted score were again included as variables. Consistent with the original analyses, slope of hearing loss entered into the regression equation only in low-pass filter conditions. Specifically, for the LP1403 Hz and LP1795 Hz conditions slope of hearing loss entered first into the regression solution accounting for 24% and 29% of the variance, respectively. SII predicted score also entered into the regression solution, accounting for an additional 3% and 5% of variance in the LP1795 Hz and LP1403 Hz conditions, respectively. The total variance accounted for by slope and SII predicted scores for these two filter conditions was the same as, or greater than, that accounted for by including low- and high-frequency average thresholds in the analysis. For the remaining low-pass filter conditions, LP2244 Hz and LP3534 Hz, slope alone entered into the regression solution; however, the amount of variance accounted for was less than for the original analysis. For the remaining high-pass, bandpass, and wideband conditions slope did not enter into the regression solution. Together, these results suggest that slope of hearing loss, apart from degree of hearing loss, affects understanding of severely low-pass filtered speech.

C. Factors affecting change in performance with changes in filter condition

Our analyses showed, as expected, that average performance improved with increasing bandwidth and, in most conditions, was affected by both degree and slope of hearing loss. However, the change in performance with each increase in bandwidth varied widely across participants. For example, when increasing the high-frequency cutoff from LP3534 Hz to wideband, individual performance changes ranged from an increase of 35.9 rau to a decrease of 40.5 rau.

The large individual differences in benefit from bandwidth changes may be due, in part, to differences in how audibility changed as bandwidth increased. Specifically, since individual thresholds and test SNRs varied between participants, it is likely that changes in audibility with bandwidth also varied between participants. Therefore improvements in understanding would also be expected to vary between participants. Stepwise multiple linear regression analyses were again used to determine the relative contributions of audibility (change in SII predicted scores), degree and configuration of hearing loss and age to performance changes with bandwidth. Results are shown in Table 3.

In most cases, none of the predictor variables entered into the regression equation. This suggests that these variables accounted for little to none of the variance observed in changes in speech understanding with bandwidth changes. An exception to this occurred when high-frequency information, between 3534–8976 Hz, was added to existing low-frequency information. Specifically, when the speech information in the 3534–8976 Hz region was provided together with information in the LP3534 Hz or BP713–3534 Hz conditions, degree of low- and high-frequency hearing loss were both significant predictors of performance changes. In both conditions, as expected, coefficients for high-frequency thresholds were negative, suggesting that as high-frequency thresholds increased benefit from the addition of high-frequency information decreased. In contrast, coefficients for low-frequency thresholds were positive suggesting benefit from high-frequency information (>3534 Hz) increased as low-frequency thresholds worsened (Table 3). In other words, given similar high-frequency thresholds, individuals with relatively flat audiograms were better able to use information in very high-frequency regions (>3534 Hz) than those with steeply sloping high-frequency losses.

An additional regression analysis, including audiogram slope (instead of low- and high-frequency thresholds), age, and change in SII predicted score, was conducted. Results were consistent with the initial analysis, with slope entering into the regression solution only in the two conditions where high-frequency (>3534 Hz) information was added to existing low- (LP3534 Hz) or mid-frequency (BP713–3534 Hz) information. Also consistent with the initial analysis, slope coefficients were negative suggesting that as slope increased, benefit from the information in the amplified high-frequency speech components decreased. However, the amount of variance accounted for by this solution was less than when degree of high- and low-frequency hearing loss were entered as predictor variables.

E. Individual variations in benefits from high-frequency speech information

Of particular clinical interest, as relevant to hearing aid applications, is the benefit provided by information within amplified high-frequency speech components. Comparison of performance in the LP3534 Hz and wideband conditions provides information about potential benefits of extending high-frequency bandwidth. The average benefit from this bandwidth increase was small (~7 rau). However, performance changes varied widely across participants (from approximately −40 rau to 36 rau). Cox et al. (1988) reported a critical difference of 15.5 rau when 2 CST passage pairs are used to obtain a score. Using this criterion to determine significant differences between the LP3534 and wideband conditions, 18 (29%) participants showed a significant improvement, 3 (5%) participants showed a significant decrement, and 41 (66%) participants showed no significant change.

Figure 5 shows that performance of some individuals was quite good in the LP3534 Hz condition. Thus, despite our attempts, ceiling effects still may have limited benefit from the addition of speech information above 3534 Hz, at least for some participants. Correlation analysis revealed that benefit when increasing bandwidth from LP3534 Hz to wideband was strongly, and negatively, correlated with the measured score for the LP3534 Hz condition ($r = -0.571$, $p<0.001$). This is consistent with the idea that ceiling effects limited benefit from speech information above 3534 Hz for some of our participants.

In an attempt to reduce ceiling effects, we included the BP713–3534 Hz condition. The removal of information below 713 Hz reduced scores, compared to the LP3534 Hz condition, and thus reduced concerns regarding ceiling effects. The average score in the BP713–3534 Hz condition (38.6 rau) was significantly lower than the average score in the LP3534 Hz condition (73.6 rau; $p < 0.05$). Comparison of performance in the BP713–3534 Hz condition with that for the HP713 Hz condition gives a measure of the benefits of extending high-frequency bandwidth in a condition with limited access to low-frequency information, as might occur when listening to speech in a low-frequency weighted noise. The average benefit (13.5 rau) from high-frequency information in this case was almost twice that observed when extending bandwidth from the LP3534 Hz condition to wideband (~7 rau). Improvements across participants ranged from approximately −28 to 41 rau. Figure 6 shows histograms of changes in CST scores (in rau) resulting from increasing the high-frequency cutoff from 3534 to 8976 Hz.

Importantly, the number of participants who benefited significantly from the addition of high-frequency information increased in this more difficult listening condition. Speech understanding increased significantly (>15.5 rau) as the upper cutoff frequency increased from 3534 to 8976 Hz for 30 (~48.4%) participants, did not change for another 30 (~48.4%) and decreased for 2 (~3.2%) participants. A correlation analysis revealed, again, a significant negative correlation between the baseline score (BP713–3534 Hz in this case) and benefit from additional high-frequency information. However, the correlation was not as strong as for the previous comparison (r= −0.292, p = 0.021). This finding is consistent with the idea that in many cases benefit from amplified high-frequency information may increase in more difficult listening conditions, if the increase in bandwidth adds audible speech information.

Table 4 shows the average audiometric characteristics of listeners whose performance significantly increased, decreased, or showed no change in performance when frequencies above 3534 Hz were added. Consistent with the results of our regression analysis, the individuals who received the most benefit had, in general, less high-frequency and more low-frequency hearing loss (shallower slopes) than other participants. It is of interest to note that the three participants who showed significant (>15.5 rau) decreases in understanding had very similar, steeply sloping high-frequency losses between 1000 and 3000 Hz. Thresholds for these participants were between 10 and 20 dB HL at 1000 Hz and were 65 to 95 dB HL at 3000 Hz. These slopes were among the steepest observed in our participants. In addition, for these participants, TEN (SPL) test results were either inconclusive or positive for dead regions for frequencies of 3000 Hz and above. Given the relatively good use of low-pass filtered speech information by individuals with steeply sloping losses, a focus on ensuring adequate mid-frequency amplification (1000–2000 Hz region) may be especially important for this group.

IV. DISCUSSION

Of primary importance, and consistent with Horwitz et al. (2008), our results show that for the vast majority of participants (95%) there was little negative consequence to providing the widest bandwidth possible, regardless of degree or configuration of hearing loss. With the exception of three listeners with steeply sloping losses, speech understanding in the widest bandwidth condition was equivalent to or better than that in any other filter condition. However, absolute performance in any given filter condition and benefit from the addition of speech information in various frequency regions varied widely among our participants.

The factor most responsible for individual variations in speech understanding in a given filter condition was degree of hearing loss. In general, as degree of hearing loss increased performance decreased. Threshold effects, however, were frequency specific with increases in LFA thresholds associated with poorer performance primarily in the low-pass and band-pass filter conditions and increases in HFA thresholds associated primarily with poorer performance in high-pass conditions. In the wideband condition, increases in both low- and high-frequency thresholds were associated with poorer than predicted scores (Table 2).

Importantly, the effects of degree of hearing loss identified in the regression analysis do not appear to reflect simple differences in audibility. If audibility was the primary factor responsible for performance differences across individuals then SII predicted score (which captures both threshold and SNR effects on audibility), and not degree of hearing loss, would have been the first factor to enter into the regression solution. That is predicted scores would have been the variable most strongly correlated with measured scores in a given filter condition but this was not the case. The fact that predicted scores generally did not enter into the regression at all, or accounted for only a small proportion of the variance in measured scores, suggests that differences in audibility were not the driving factor behind differences in measured scores (within a given filter condition) in our group. Although these results are not surprising, the literature on the effects of degree of hearing loss on speech understanding is mixed.

Humes (2007) recently reviewed a series of studies which examined, in part, the relationship between degree of hearing loss, audibility and speech understanding in persons with mild-moderate SNHL. A general conclusion from the review was that, when audibility differences were accounted for, the relationship between degree of hearing loss and broadband speech understanding was often weak. This is consistent with results from a substantial literature showing that, when audibility is equated, the speech understanding of listeners with *mild-to-moderate* hearing loss is often quite similar to that of individuals without hearing loss (e.g., Fabry and Van Tasell 1986; Zurek and Delhorne 1987; Humes and Roberts 1990; Dubno and Schaefer 1992; Humes 2007).

In the current study, an amplification scheme designed to provide audibility over a wide frequency range for all participants, regardless of their degree of loss, was used. In addition, a measure of audibility (SII predicted score) was included to account for residual differences in audibility across participants. In contrast to Humes (2007), results from our regression analyses showed that degree of hearing loss was the strongest predictor of performance in most filter conditions. The strong influence of degree of hearing loss on our results, despite ensuring access to audible information over a wide frequency range, is likely due to the inclusion of listeners with more severe hearing loss than those reported by Humes (2007). The participants in the studies reviewed by Humes (2007) had mild-to-moderate high-frequency SNHL (HFA at 2, 3 and 4 kHz <65 dB HL). In the current study, bilateral HFA thresholds (2, 3 and 4 kHz) ranged from 33 to 105 dB HL with 45% of participants having HFA thresholds above 65 dB HL. The finding of an inverse relationship between degree of hearing loss and speech understanding is consistent with other work examining listeners with more severe hearing loss (e.g., Pavlovic 1984; Pavlovic et al. 1986; Ching et al. 1998; Sherbecoe and Studebaker 2003). Although degree of loss was found to be the strongest predictor of performance in a given filter condition, the final regression models accounted for only 22% to 44% of the variance in scores suggesting that additional factors (e.g., cognitive abilities) contribute to performance differences in these conditions.

Another finding of interest from the current study was the effect of configuration of hearing loss on the utility of amplified speech information. Regression results suggested that, given equivalent low-frequency thresholds, individuals with steeply-sloping losses may make better use of information in severely low-pass filtered speech than individuals with moderate-sloping or flat hearing losses (See Table 2). The reason for this differential benefit from low-frequency speech information is not clear. There is limited research suggesting that listening experience may affect the ability to make use of low-pass filtered speech information. Boothroyd (1967) investigated this possibility using filtered speech for 25 children with varying degrees of high-frequency hearing loss. He noted that four children in the study had better understanding of low-pass filtered speech than that of average adults without hearing loss. The four children all had normal or near normal hearing at low frequencies. This better-than-normal understanding was assumed to be due to the experience these children had listening to low-pass filtered speech as a result of their long standing high-frequency hearing loss. In a later publication, Boothroyd (1978) suggested these differences were small and could have been reduced if the normal hearing subjects had received more training on the low-pass filtered speech materials.

More recent work suggests that the presence of high-frequency cochlear dead regions may be associated with an increased ability to use low-frequency information (Vestergaard, 2003; Moore and Vinay, 2009). Although not a universal finding, the presence of a steeply sloping high-frequency hearing loss is often associated with high-frequency dead regions (e.g., Moore 2004). Moore and Vinay (2009) suggests that the presence of high-frequency cochlear dead regions may lead to cortical reorganization and result in over-representation of low-frequency sounds, potentially enhancing the utility of low-frequency speech information. To examine this question they assessed auditory perception in participants with and without high-frequency dead regions starting at 1000 or 1500 Hz. The authors assessed frequency discrimination and modulation detection of low-frequency stimuli and consonant recognition of low-pass filtered speech. Individuals with high-frequency dead regions showed enhanced frequency and amplitude processing in the lower frequency regions and better understanding of low-pass filtered speech than individuals without high-frequency dead regions.

In the current study the edge frequency and extent of dead regions among our participants could not be clearly defined due, in part, to the large number of inconclusive test results. There are several factors that may have contributed to the number of inconclusive test results observed in this study including the use of a 5 dB step size during threshold assessment. While some early work with the TEN (SPL) utilized a 5 dB step size (e.g., Moore et al., 2003), more recent work suggests that the use of a smaller (2 dB) step size may reduce inconclusive results, false positive results and, potentially, increase test reliability (Cairns et al., 2007). In addition, the ER-3A insert earphones used in this study have a substantial roll-off above 4000 Hz. This steep roll off would have reduced the masking effectiveness of the TEN in these frequency regions potentially limiting the reliability of TEN (SPL) results (Moore, 2004). Thus the role dead regions played in our study results remains unclear. It should be noted, however, that the presence of a high-frequency dead region may not be a prerequisite for enhanced low-frequency processing. The presence of a steeply-sloping high-frequency loss would result in reduced auditory input to high-frequency regions, regardless of whether high-frequency dead regions were present. This reduced input could lead to cortical changes (e.g., Thai-Van et al. 2007; Eggermont 2008).

Also of direct clinical interest were the findings relating slope of hearing loss to benefit from amplified high-frequency (>3534 Hz) speech information. Consistent with previous findings from our laboratory (Hornsby and Ricketts 2003, 2006), regression results suggested that, given similar high-frequency thresholds, individuals with flat or moderately sloping hearing loss benefited more from information in amplified high-frequency speech components than individuals with steeply-sloping hearing losses.

Finally, it is worth reiterating the strong negative correlation observed between benefit from access to information in amplified high-frequency (>3534 Hz) speech components and baseline performance for the narrower bandwidth (LP3534 or BP713–3534 Hz) conditions. This finding, also consistent with Turner and Henry (2002), suggests that the benefit from amplified high-frequency speech components depends, in part, on an individual’s speech understanding abilities without access to information in that frequency region. Specifically, the benefit from amplification of high-frequency speech components is largest in conditions where performance for the narrower bandwidth (< 3534 Hz) is poor, such as for listeners with flat hearing loss or when listening in low-frequency weighted noise. Individuals with poor understanding are less likely to be limited by ceiling effects and thus have the most potential to benefit from information provided by amplification of high-frequency speech components.

These findings have implications for hearing aid prescriptive fitting formulas. In general, the results suggest that, across a wide range and configuration of hearing losses, access to high-frequency (3534–8976 Hz) speech information is needed to achieve optimal intelligibility. This information may be particularly important for individuals with relatively poor understanding due to degraded auditory processing abilities across a wide frequency range (i.e., flat hearing losses) or to poor listening conditions (e.g., poor SNR, particularly at low frequencies).

Acknowledgments

This work was supported, in part, by Grant R03 DC006576 from the National Institute on Deafness and Other Communication Disorders (National Institutes of Health) and the Dan Maddox Hearing Aid Research Foundation. We would like to thank the associate editor Karen Doherty, Brian C. J. Moore and two anonymous reviewers for their helpful comments on earlier versions of this manuscript. We also thank Drew Dundas, Jason Galster, and Elise Neukom for their assistance with this project.

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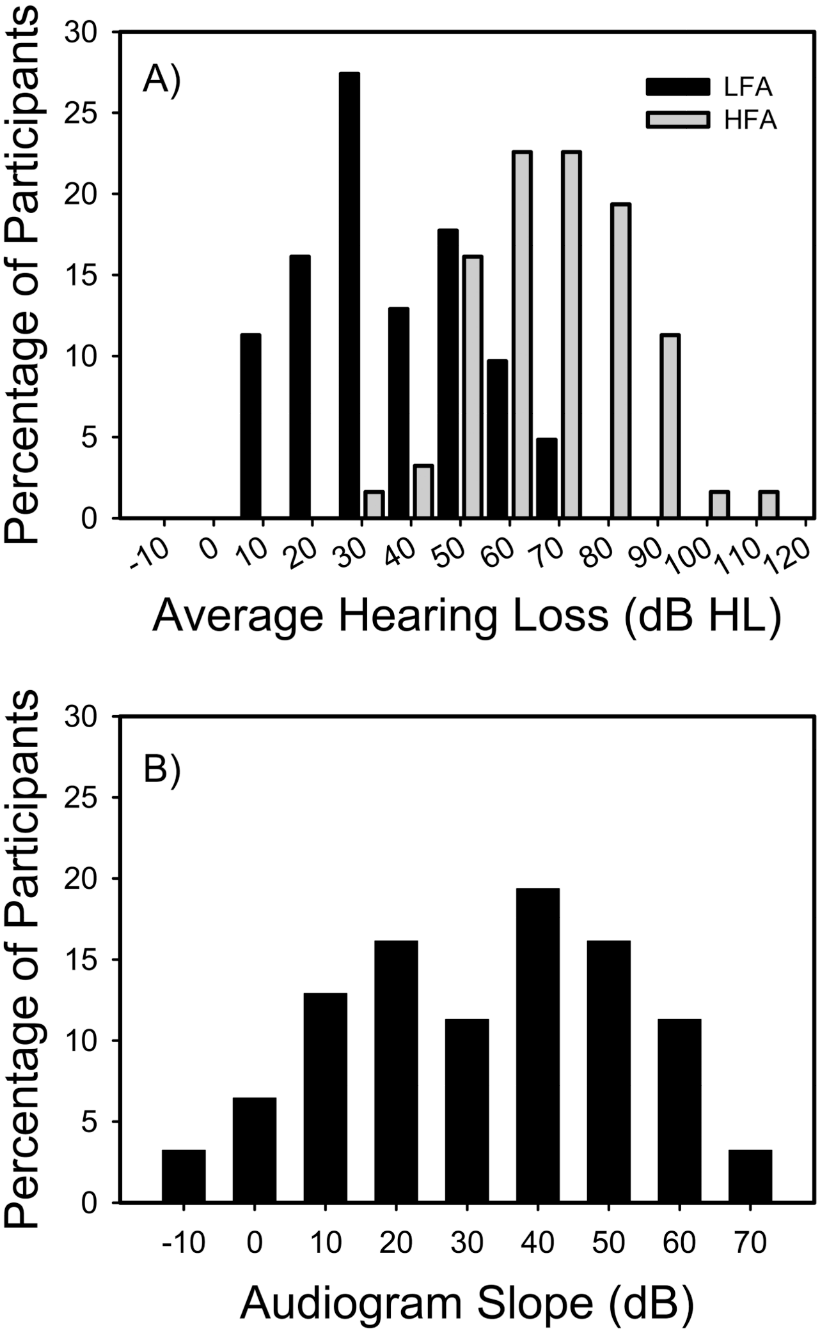

Figure 1.

Distribution of low- and high-frequency average thresholds in dB HL (Top Panel) and the distribution of slope values (Bottom Panel) for participants with hearing loss.

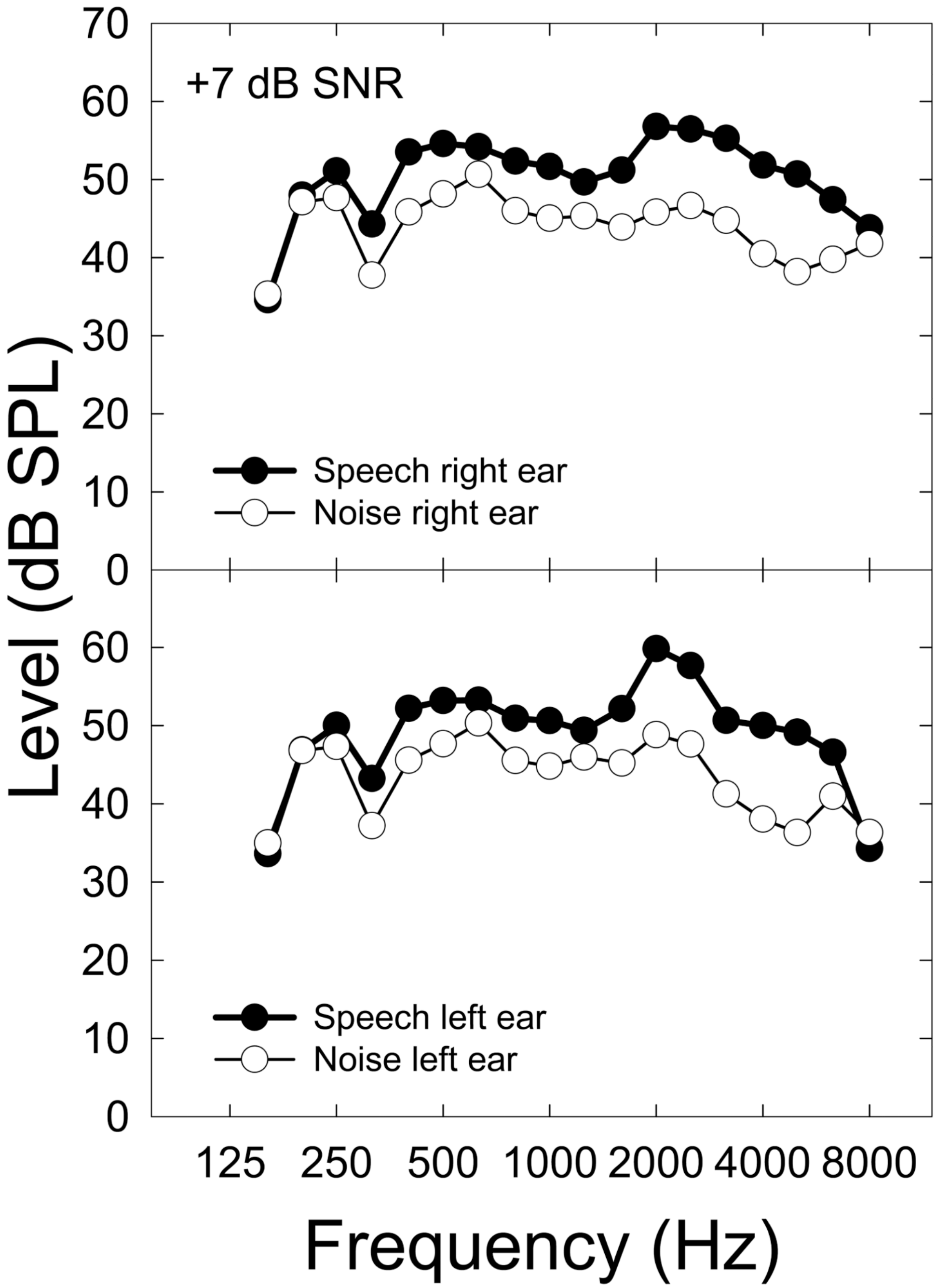

Figure 2.

1/3rd octave band levels of speech and noise measured at KEMAR's ears prior to shaping for a given hearing loss. The wideband rms level is 65 dB SPL for the speech and 58 dB SPL for the noise (+7 dB SNR).

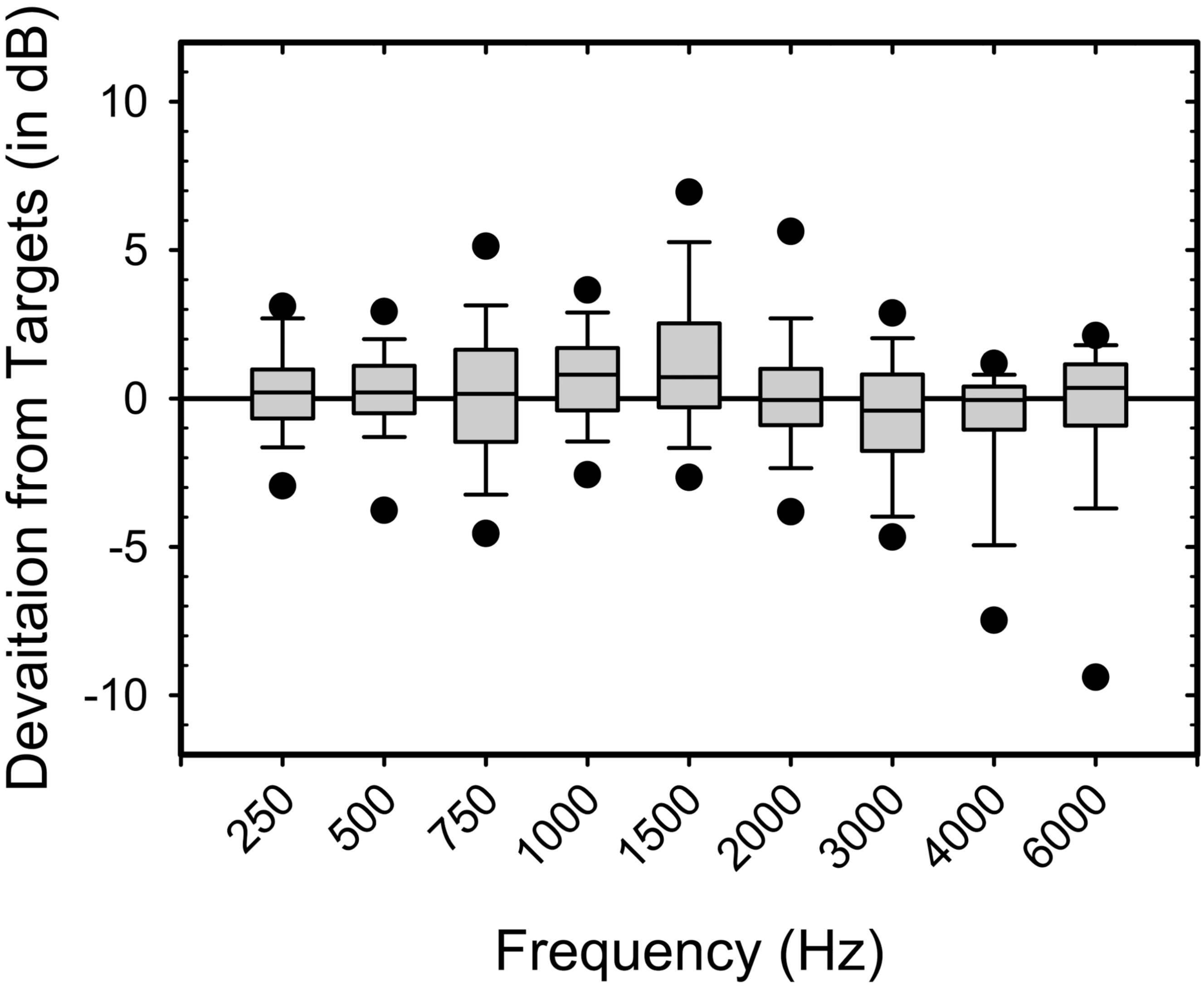

Figure 3.
Box and whisker plot showing deviations from real ear targets in dB. Targets are modifications of DSL 4.1 targets (see text for details). Boxes indicate the 25th and 75th percentiles and the line within the box marks the median. Error bars indicate the 90th and 10th percentiles and the filled circles indicate the 5th and 95th percentiles.

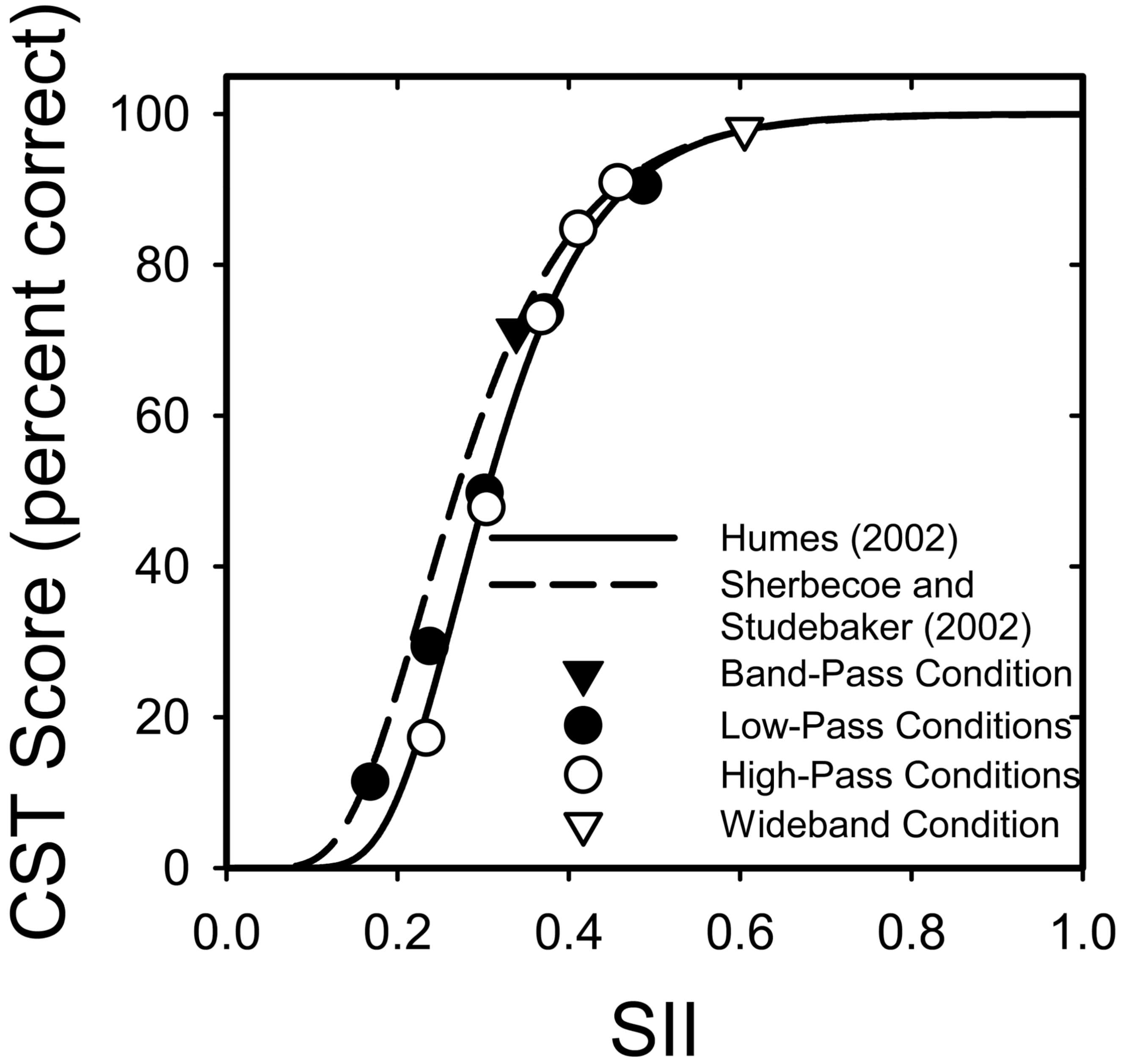

Figure 4.

Average CST performance versus SII for participants with normal hearing. Each symbol represents average performance in a given filter condition. Open and filled circles represent high-pass (713, 1114, 1426, 1783, and 2228 Hz) and low-pass (898, 1403, 1795, 2244 and 3534 Hz) conditions, respectively. Open and filled triangles represent the wideband (143–8976 Hz) and band-pass (713–3534 Hz) conditions, respectively. The solid and dashed lines show transfer functions for the CST derived by Humes (2002) and Sherbecoe and Studebaker (2002), respectively.

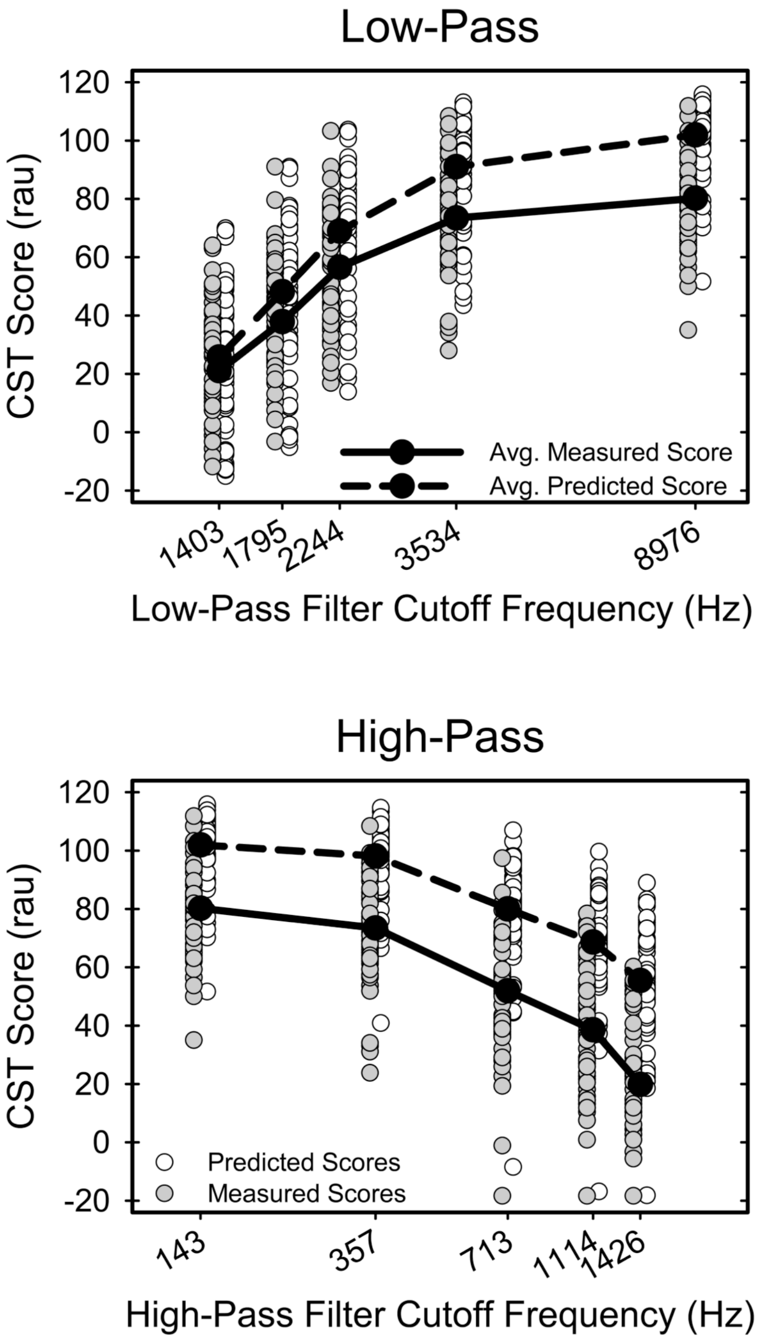

Figure 5.

Measured (grey circles) and predicted (open circles) CST scores in rau as a function of low- (upper panel) or high- (lower panel) pass filter cutoff frequency. The high-pass 143 Hz and low-pass 8976 Hz data points are the same and show performance for the wideband condition (143–8976 Hz). The solid and dashed lines show average measured and SII predicted performance. Measured and predicted data points for each filter condition are slightly offset for clarity.

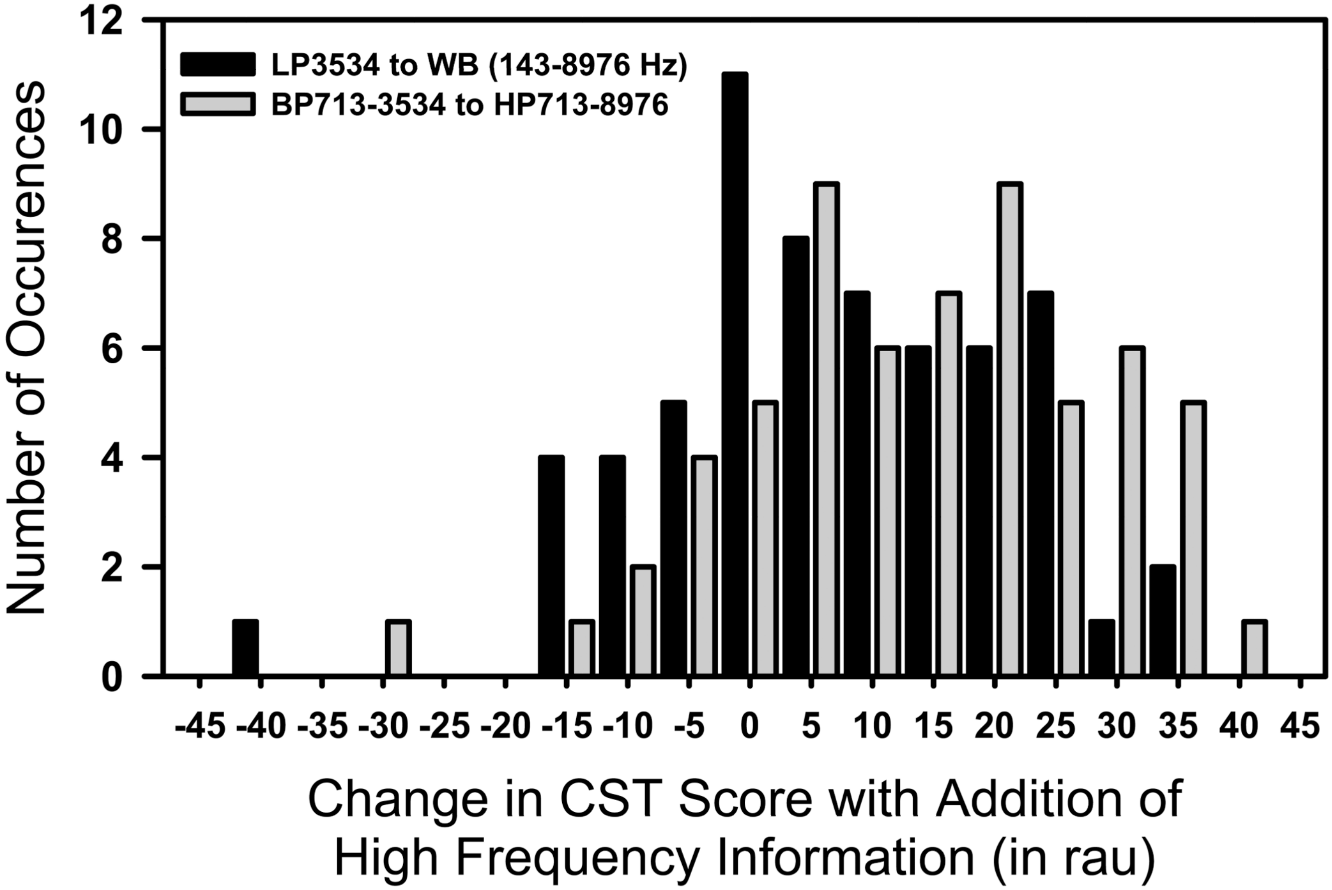

Figure 6.

Histograms of change in CST scores (in rau) with the addition of high frequency speech information (>3534 Hz). Black bars show the change in score when the filter condition changed from 143–3534 Hz to 143–8976 Hz. Grey bars show the change in score when the filter condition changed from 713–3534 Hz to 713–8976 Hz.

Table 1

Results of a correlation analysis between predictor variables. LFA= bilateral, low-frequency (250, 500 and 1000 Hz) average; HFA= bilateral, high-frequency (3000, 4000 and 6000 Hz) average; LP = low-pass; HP = high-pass; BP= bandpass (713–3534 Hz); WB = wideband (143–8976 Hz).

				Low Pass and Wideband Predicted Scores				
	Age	**LFA**	**HFA**	**LP1403**	**LP1795**	**LP2244**	**LP3534**	**WB**
Age	1	0.253*	−0.004	0.307*	0.302*	0.289*	0.292*	0.282*
LFA	0.253*	1	0.249	0.095	0.053	0.02	−0.003	−0.072
HFA	−0.004	0.249	1	.354**	.318*	.267*	0.159	−0.049

				High Pass and Band Pass Predicted Scores				
	Age	LFA	HFA	HP357	HP713	HP1114	HP1426	BP
Age	1	0.253*	−0.004	0.277*	0.270*	0.267*	0.268*	0.298*
LFA	0.253*	1	0.249	−0.089	−0.131	−0.135	−0.114	−0.058
HFA	−0.004	0.249	1	−0.093	−0.203	−0.262*	−0.323*	0.074

[*] Correlation is significant at the 0.05 level (2-tailed).

[**] Correlation is significant at the 0.01 level (2-tailed).

Table 2

Results of stepwise linear regression analyses for different filter conditions. Each column represents a filter condition and includes regression coefficients (if significant; $p<0.05$). The order of entry (1st, 2nd, 3rd, etc…) of a specific predictor variable into the regression equation is shown in ( ). Values within [ ] show the proportion of variance accounted for by the regression model with the inclusion of the listed variable and any preceding variables. Both the adjusted r^2 and total variance (1st and 2nd values in [ ], respectively) are shown. NA means the variables did not significantly improve model predictions.

	Low-pass and Wideband Filter Conditions				
	LP1403 Hz	**LP1795 Hz**	**LP2244 Hz**	**LP3534 Hz**	**Wideband**
SII Pred.	(1) 0.250 [0.11/0.12]	(3) 0.200 [0.32/0.35]	(2) 0.252 [0.24/0.27]	(2) 0.248 [0.26/0.29]	NA
HFA	(3) 0.431 [0.28/0.32]	(2) 0.494 [0.28/0.31]	NA	NA	(1)-0.425 [0.21/0.23]
LFA	(2)-0.467 [0.20/0.23]	(1)-0.572 [0.12/0.13]	(1)-0.478 [0.17/0.18]	(1)-0.516 [0.22/0.23]	(2)-0.216 [0.25/0.28]
Age	NA	NA	NA	NA	NA
Constant	2.0	15.2	56.5	69.6	117.2
	High-pass and Band-pass Filter Conditions				
	HP1426 Hz	HP1114 Hz	HP713 Hz	HP357 Hz	BP713-3534 Hz
SII Pred.	NA	NA	(2) 0.345 [0.29/0.31]	NA	NA
HFA	(1)-0.844 [0.36/0.37]	(1)-0.813 [0.33/0.34]	(1)-0.642 [0.25/0.26]	(1)-0.449 [0.19/0.21]	NA
LFA	NA	(2)-0.338 [0.37/0.39]	NA	(2)-0.300 [0.26/0.28]	(1)-0.582 [0.21/0.22]
Age	(2)-0.548 [0.42/0.44]	NA	(3) −0.550 [0.34/0.37]	NA	NA
Constant	116.7	106.6	107.7	115.1	59.6

Table 3

Results of stepwise multiple regression analyses on change in scores with change in filter cutoff frequency. For example, the BP713-3534 Hz to HP713 Hz column shows results when examining the change in performance as information between 3534–8976 Hz was added to lower frequency information (BP713-3534 Hz). Coding is the same as in Table 2.

	Add High-Frequency Information				
	LP1403-1795 Hz	**LP1795-2244 Hz**	**LP2244-3534 Hz**	**LP3534-8976 Hz**	**BP713-3534 to HP713 Hz**
SII Pred.	NA	NA	(1) 0.476 [0.050.070]	NA	NA
HFA	NA	(1) 0.494 [0.09/0.10]	NA	(1) −0.525 [0.19/0.21]	(1) −0.511 [0.19/0.20]
LFA	NA	NA	NA	(2) 0.324 [0.32/0.34]	(2) 0.336 [0.33/0.35]
Age	NA	NA	NA	NA	NA
Constant	NA	37.9	6.4	31.0	36.3
	Add Low-Frequency Information				
	HP1426-1114 Hz	HP1114-713 Hz	HP713-357 Hz	HP357-143 Hz	BP713-3534 to LP3534 Hz
SII Pred.	NA	NA	NA	NA	NA
HFA	NA	(1) 0.180 [0.06/0.08]	NA	NA	(2) 0.261 [0.13/0.16]
LFA	NA	NA	NA	NA	NA
Age	NA	NA	NA	NA	(1) 0.502 [0.08/0.10]
Constant	NA	1.1	NA	NA	−18.8

Table 4

Audiometric characteristics of participants whose performance decreased significantly, did not change, or increased significantly when increasing the high-frequency cutoff to 8976 Hz. N = number of individuals in that group. Average Benefit = average change in score when bandwidth increased. PTA = pure-tone average. LFA = low-frequency average. HFA = high-frequency average. Slope = HFA-LFA.

LP3534 Hz to Wideband

N	**Group**	**Average Benefit (rau)**	**PTA**	**LFA (dB)**	**HFA (dB)**	**Slope**
3	Did Worse	−25.0	35.6	25.6	82.2	56.6
41	No Benefit	1.8	43.1	35.3	70.5	35.2
18	Did Better	23.5	44.9	40.5	61.5	21.0

BP713-3534 Hz to HP713 Hz

N	Group	Average Benefit (rau)	PTA	LFA (dB)	HFA (dB)	Slope
2	Did Worse	−22.3	31.7	25.0	85.8	60.8
30	No Benefit	4.1	42.6	34.3	73.5	39.2
30	Did Better	25.2	44.7	39.0	62.5	23.5