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The effect of hearing aid bandwidth and configuration of hearing loss on bimodal speech recognition in cochlear implant users.

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Abstract

Objectives: (1) To determine the effect of hearing aid bandwidth on bimodal speech perception in a group of unilateral cochlear implant (CI) patients with diverse degrees and configurations of hearing loss in the non-implanted ear, (2) To determine whether there are demographic and/or audiometric characteristics that would help to determine the appropriate hearing aid (HA) bandwidth for a bimodal patient.

Design: Participants were 33 experienced bimodal device users with post-lingual hearing loss. Twenty-three of them had better speech perception with the CI than the HA (CI>HA group) and 10 had better speech perception with the HA than the CI (HA>CI group). Word recognition in sentences (AzBio sentences at +10 dB SNR presented at 0° azimuth) and in isolation (CNC words) was measured in unimodal conditions (CI alone or HAWB, which indicates HA alone in the wideband condition) and in bimodal conditions (BMWb, BM2k, BM1k, BM500) as the bandwidth of an actual hearing aid was reduced from wideband (WB) to 2 kHz, 1 kHz, and 500 Hz. Linear mixed effect modeling was used to quantify the relationship between speech recognition and listening condition, and to assess how audiometric or demographic covariates might influence this relationship in each group.

Results: For the CI > HA group, AzBio scores were significantly higher (on average) in all bimodal conditions than in the best unimodal condition (CI alone), and were highest at the BMWb condition. For CNC scores, on the other hand, there was no significant improvement over the CI-alone condition in any of the bimodal conditions. The opposite pattern was observed in the HA > CI group. CNC word scores were significantly higher in the BM2k and BMWb conditions than in the best unimodal condition (HAWB), but none of the bimodal conditions were significantly better than the best unimodal condition for AzBio sentences (and some of the restricted bandwidth conditions were actually worse). Demographic covariates did not interact significantly with bimodal outcomes, but some of the audiometric variables did. For CI > HA participants with a flatter audiometric configuration and better mid-frequency hearing, bimodal AzBio scores were significantly higher than the CI-alone score with the wide-band setting (BMWb) but not with other bandwidths. In contrast, CI > HA participants with more steeply sloping hearing loss and

poorer mid-frequency thresholds (> 82.5 dB) had significantly higher bimodal AzBio scores in all bimodal conditions, and the BMWB did not differ significantly from the restricted bandwidth conditions. HA>CI participants with mild low frequency hearing loss showed the highest levels of bimodal improvement over the best unimodal condition on CNC words. They were also less affected by HA bandwidth reduction compared to HA>CI participants with poorer low frequency thresholds.

Conclusions: The pattern of bimodal performance as a function of the HA bandwidth was found to be consistent with the degree and configuration of hearing loss for both patients with CI>HA performance and for those with HA>CI performance. Our results support fitting the HA for all bimodal patients with the widest bandwidth consistent with effective audibility.

Introduction

With the changing criteria for cochlear implant candidacy, increasing numbers of people with a unilateral cochlear implant (CI) have usable acoustic hearing in the non-implanted ear. It is now generally agreed upon that when there is aidable hearing in the non-implant ear, unilateral CI recipients should continue to use a hearing aid (HA) in that ear (Ching et al. 2004; Dorman and Gifford 2010; Offeciers et al. 2005). When a person with a unilateral CI uses a HA in the non-implanted ear, he/she receives bimodal stimulation. The CI provides an electrical signal to make acoustic information available to the implanted ear and the HA amplifies and sends acoustic information to the non-implanted ear. It is well established that many who use both devices are able to integrate the information provided and can enjoy several types of benefits. These benefits include: (a) improved speech recognition performance in quiet and noise (Ching et al. 2004; Gifford et al. 2007; Dorman and Gifford 2010; Zhang et al. 2010), (b) improved sound quality (Armstrong et al. 1997; Ching et al. 2004; Flynn and Schmidtke 2004; Potts et al. 2009), (c) some advantages of bilateral hearing (Ching et al. 2004; Davidson et al. 2015; Firszt et al. 2012; Gifford et al. 2014; Morera et al. 2012; Morera et al. 2005; Schafer et al. 2011; Schafer et al. 2007), and (d) improved quality of life (Farinetti et al. 2015; Van Loon et al. 2017).

What is not necessarily agreed upon is the best way to fit the HA to be used by bimodal patients. Recent surveys of “cochlear implant audiologists” in multiple centers in Europe (Scherf and Arnold 2014), the United States (Siburt and Holmes 2015), and Great Britain (Fielden and Kitterick 2016) reveal that there is no standard clinical approach to coordinating the fitting of the HA to be used in the contralateral ear of unilateral CI recipients. A common problem identified by these surveys is that in many cases, the CI is fit by one audiologist and the HA by a different audiologist (often at a different facility). When this happens, it is often unknown how the HA was fit (e.g., standard prescriptive procedure, proprietary fitting strategy, alternate fitting strategy) or how the settings in each device interact to affect bimodal performance.

Among bimodal patients, there are many possible audiometric configurations in the non-implanted ear. Hearing can differ in terms of slope and/or degree of hearing loss. Recent research also supports provision of a cochlear implant in persons with significant asymmetry in hearing, i.e., very poor hearing in one ear (potential implant ear) and substantial hearing

and good speech recognition performance in the non-implanted ear (Arndt et al. 2017; Cadieux et al. 2013; Firszt 2008; Firszt et al. 2012; Leigh et al. 2016; Plant, Van Hoesel, et al. 2016; Sanhueza et al. 2016; Van Loon et al. 2017; Vermeire and Van de Heyning 2009). It seems likely that the benefit that can be obtained from the HA will be related to the amount of residual hearing in the non-implant ear. However, it has been suggested that the primary benefit from the HA is from access to information not readily accessible through the CI—information that can be obtained from amplification of low frequencies. Several hypotheses have been put forward regarding mechanisms by which an acoustically delivered signal may enhance speech perception in cochlear implant patients. The most direct hypothesis is that the acoustic signal carries phonetic information that is not present in the electrical signal and that contributes directly to speech perception (e.g., Mok et al., 2006, Kong and Carlyon, 2007). In particular, the acoustic signal may carry information about voicing and manner of articulation, as well as vowel first formant frequency. Much of this information (including voicing and manner of articulation) may be provided by F0 alone (c.f., Brown and Bacon, 2010), but additional place, manner, and vowel formant frequency information is provided by frequencies above F0 (Sheffield and Zeng, 2012). In addition to phonetic information, the acoustic signal may contain prosodic cues to help speech perception, some of which (like F0) are not well perceived by most CI users. Other hypotheses propose indirect mechanisms which may be particularly useful for speech perception in noise. For example, the acoustic signal may facilitate a “glimpsing” process to take advantage of short temporal windows when the signal-to-noise ratio is most favorable. Another possibility is that enhanced F0 perception via the acoustic signal may be used to facilitate separate streaming of different signals (Turner et al., 2004, Kong et al, 2005, Qin and Oxenham, 2005, Qin and Oxenham, 2006), or facilitate lexical segmentation (Spitzer et al., 2009). These various hypotheses are complementary rather than exclusive, and they may apply in different situations. For example, the direct phonetic hypothesis is much more likely to be relevant for identification of monosyllabic words in quiet than the indirect hypotheses.

While a standard approach to fitting the HA is to provide amplification over as wide a bandwidth as possible, several studies have suggested that restricting the bandwidth of the HA might improve bimodal benefit. In an early study of bimodal benefit for adults with severe-to-profound hearing loss in the non-implanted ear, Mok and colleagues (Mok et al. 2006) found that the primary benefit of the HA was from amplification of low frequencies. Based on the performance of several subjects who had poorer performance in the bimodal condition than the CI-alone condition, they suggested that provision of amplification in the mid and high frequency region might actually interfere with the signal from the CI. They proposed that a mismatch in the place of excitation on the cochlea between the signals received in the two ears interfered with bimodal performance and might explain the variability in bimodal performance by persons with different degrees of hearing loss. Two other reports support the possibility that restricting the hearing aid bandwidth might improve bimodal speech recognition. (Zhang et al. 2014) tested the non-implanted ear of 22 bimodal patients with steeply sloping hearing loss to identify dead regions in the cochlea. They found that those who had dead regions in the cochlea obtained improved bimodal speech recognition performance if the amplified signal was limited to frequencies below the dead region. A wideband frequency response (NAL-R) yielded better bimodal speech recognition

in those without cochlear dead regions. Messersmith et al. (2015) reported on several patients whose bimodal speech recognition (contralateral HA fit to NAL-NL1 prescriptive targets) was poorer than with the CI alone. Reducing amplification above 2000 Hz resulted in improved bimodal performance. Since the patients in question had thresholds at 2kHz

110 dB HL, they suggested that the degraded bimodal performance might be due to amplification of frequencies at dead regions in the cochlea.

When considering amplification for the non-implant ear of bimodal patients, what HA bandwidth will provide improved performance over unimodal listening? Is the wideband HA fitting most appropriate, or would a restricted bandwidth actually be a better approach for the bimodal fitting? If so, what factors would determine the bandwidth most appropriate for the HA fitting of the bimodal patient? There have been several studies that systematically assessed the effect of the bandwidth of the acoustic signal on bimodal speech intelligibility (when the electrical signal is sent to one ear and the acoustic signal to the contralateral ear). In these studies, frequency shaping of the acoustic signal was provided to account for each subject's hearing loss based on standard prescriptive procedures, and filtered acoustic signals were presented through an insert earphone. Using this methodology, Zhang et al. (2010) investigated bimodal performance of nine bimodal patients with relatively steeply sloping hearing loss in the non-implant ear (thresholds 60 dB HL at audiometric frequencies through 500 Hz and severe-to-profound hearing loss at 1kHz and above). The acoustic signal sent to the non-implant ear was low-pass filtered (125, 250, 500, 750 Hz) or left unprocessed (wideband). The frequency-gain response for each subject was set to NAL-RP prescriptive targets. They found that the majority of bimodal benefit could be attributed to access to the acoustic signal below 125 Hz (although performance did gradually improve as the bandwidth was increased). Since the bimodal subjects in this study were a specialized sub-population with quite good low frequency hearing and steeply sloping hearing loss, the contribution of low-frequency information to bimodal benefit may be over-estimated and the contribution of mid and high-frequency information underestimated.

In a study designed to obtain further information about the contribution of low-pass and band-pass filtered acoustic signals to bimodal performance, Sheffield and Gifford (2014) assessed the performance of 12 bimodal patients (all with non-implant ear thresholds 80 dB HL at frequencies up to and including 500 Hz) using several low-pass and band-passed filtered conditions (<125, <250, <500, <750, 125–250, 250–500 and 250–750 Hz), as well as an unprocessed condition. The frequency-gain response for each listener (linear amplification) was set to the NAL-NL1 target for average conversational speech level. They established that it was not necessary to provide information below 250 Hz in the acoustic signal in order to obtain bimodal benefit: the bandpass filter condition of 250–750 Hz resulted in significant bimodal benefit. This finding is applicable to clinical HA fittings. Performance in the wideband condition did not differ significantly from the 750 Hz condition. Given the small number of subjects in the study and the fact that only three of the 12 participants had thresholds better than 90 dB HL at 2000 Hz and above, it would be important to determine whether bimodal patients with better hearing in the mid and high frequencies integrate information from these frequencies with the signal from the HA to obtain increased bimodal performance.

In addition, an important consideration relevant to the application of these findings to the fitting of hearing aids is that commercial HAs do not necessarily provide gain below 200 Hz, and their filter roll offs are significantly more shallow than the 90 dB/octave used in the two studies referenced here. There is no question that both studies yielded information that may be important to help optimize bimodal fittings, but at some point it is important to conduct similar research with actual clinically usable amplification where “off-frequency” amplification may be available due to shallower filter skirts of the HA.

In an earlier study, we systematically examined the effect of the HA bandwidth on bimodal speech perception in 14 adult bimodal patients with severe to profound sensorineural hearing loss in the non-implanted ear (Neuman and Svirsky 2013). Participants were chosen such that it was possible to provide amplification over a relatively wide bandwidth; unaided thresholds no poorer than 95 dB HL through 2000 Hz and no poorer than 115 dB HL at 4000 Hz. The “wideband” frequency response of the HA was set based on the NAL-RP prescriptive targets (Byrne et al. 1990, 1991). Alternative fittings systematically reduced the frequency range of amplification by turning off the gain in the HA software using upper cutoff frequencies of 2000, 1000 and 500 Hz. Speech recognition testing was carried out using sentence materials in quiet or in noise [AzBio Sentence Test, (Spahr et al. 2012)]. On average, this group of bimodal device users benefited from access to mid-frequency acoustic information. For the group, the HA response up to and including 2000Hz was the minimum bandwidth required for bimodal benefit in quiet and in noise. There was no advantage to providing amplification only to lower frequencies (below 1000 Hz). Results showed that listeners with usable hearing in the mid-frequency region could integrate information from the HA with the signal provided by the CI in the contralateral ear to obtain bimodal benefit.

The purpose of the present study is to further examine the effect of hearing aid bandwidth on bimodal speech perception when bandwidth is manipulated using the type of filtering available in a real hearing aid. We obtained data from participants with diverse degrees and configurations of hearing loss in order to determine how audiometric characteristics and/or demographic factors might interact with bimodal performance as a function of HA bandwidth.

Methods

This study was approved by the Institutional Review Board of the New York University School of Medicine. All subjects were recruited and participated willingly with informed consent obtained.

Participants

Thirty-three adult bimodal listeners participated in the study. Participants were recruited through the distribution of fliers describing the study to clients at the NYU Cochlear Implant Center and at other local centers. All subjects had post-lingual hearing loss, at least 6 months experience using their CI, and reported consistent daily use of their HA. All had full-insertion electrodes in the implanted ear. Only one of the participants had residual hearing in the implanted ear. In order to qualify for inclusion in the study, subjects were required to obtain a score of 25 or higher on the Mini-Mental State Exam (Folstein et al. 1975). This test

was used to rule-out cognitive impairment and the score of 25 is consistent with normal cognitive function.

While for the majority of our participants, performance with the CI alone was higher than with the HA alone, approximately 30% of our participants had better speech recognition performance with the HA than with the CI. Participants were divided into two groups based on best unimodal performance on the AzBio sentences in noise (+10 dB SNR): (1) CI performance better (CI>HA) or (2) HA performance better (HA>CI). Although in a few cases the difference was small, none of the subjects had equal AzBio scores in both ears. Audiograms are shown separately for those with CI better performance (Figure 1a) and those with HA better performance (Figure 1b). As can be seen, participants in both groups had a wide range of residual hearing in the non-implanted ear.

On average, the two groups differed with regard to pre-operative thresholds and speech recognition performance in the CI ear before implantation. In the CI>HA group, the mean pure tone average (PTA) of the HA ear was 72.5 dB HL (SD, 16 dB) and the aided CNC score was 38% (SD, 23%). The mean pre-op PTA in the CI ear was 89 dB HL (SD, 14 dB), and the aided CNC score was 11.8% (SD, 14.5%). The HA>CI group had substantial usable hearing in one ear, and very poor hearing in the ear that was later implanted. The mean pre-op PTA in the HA ear was 49 dB (SD, 17.7 dB), and the mean aided CNC score was 74% (SD, 20%). The mean pre-op PTA in the CI ear was 100 dB HL (SD, 22.5 dB) and the mean aided CNC score was 10.3% (SD, 11.6%).

Table 1 summarizes demographic information of the participants by group. A comparison of age, demographic and audiometric profiles of the non-implant ear by group is provided in Table 2. Age, CI experience and HA experience did not differ significantly between groups. The CI>HA group has poorer hearing than the HA>CI group. The average slope of the audiogram was not found to be significantly different, even though the HA>CI slope was shallower than the slope for the CI>HA group.

Programming and Verification of the Hearing Aid

As described in a previous study (Neuman and Svirskey (2013), in order to maintain systematic control over the characteristics of the hearing aid and to use a common prescriptive procedure for all subjects, a commercially available hearing aid (either the Siemens Motion 700 or the Siemens Nitro 701 SP) was fit and was used only for testing in the laboratory. Testing was done acutely, as the hearing aid was used only during the test session. Participants continued to use their personal hearing aids at all other times. The two models of the HA are similar in design. Both have 16 independent channels which allows a systematic method of controlling the frequency-gain response and the bandwidth of the HA. They differ in full on-gain (the Nitro provides more gain thus is more appropriate for fitting persons with severe or profound hearing loss) and in the upper frequency range (the Nitro high frequency limit is 5900 Hz, while the Motion high frequency limit is 7100 Hz). The use of these HAs provided the capability of fitting the full range of hearing losses in the non-implanted ear of our participants.

Four frequency responses were programmed into the experimental HA using Connexx 6.4.2 software. The wideband frequency response was programmed to match NAL-RP targets (Byrne et al. 1990). Because the focus of this study was only on the effect of the bandwidth of the HA on bimodal performance for average conversational speech level, compression was set to 1.0 (except for compression limiting) and all other signal processing (e.g., noise reduction) was turned off. Since speech was presented at 65 dB SPL (as detailed below) it is very unlikely that compression would have influenced the present results.

The NAL-RP prescriptive procedure was used for continuity with our previous work (Neuman and Svirsky 2013). The prescription is appropriate for all degrees of hearing loss as it includes modifications to the frequency-gain response related to the degree and configuration of hearing loss. Specifically, the gain rule changes (from half-gain to two-thirds gain) as the pure tone hearing loss exceeds 60 dB HL. When the threshold at 2000 Hz exceeds 95 dB, the shape of the frequency response changes: gain is boosted at 250 and 500 Hz and is decreased at 2000 Hz and higher frequencies (Byrne et al. 1990). This prescription has also been used in other research investigating HA fitting for bimodal patients (Zhang et al. 2010). For the 65 dB speech input level used in this experiment, the frequency response is similar to that prescribed using the NAL-NL1 prescription (Byrne et al. 2001). The NAL-NL1 prescription has also been used in other bimodal studies (Fowler et al. 2016; Sheffield and Gifford 2014).

Real-ear insertion gain (REIG) measurements were obtained to verify match to NAL-RP targets for 25 of the participants using the Interacoustics Affinity 2.0 HA analyzer (ISTS signal, International Speech Test Signal). Adjustments were made to the gain in each of 16 channels of the hearing aid using the Connexx software to match targets as closely as possible. This wideband HA setting was saved as Program 1 (BMWB, also HAWB). Three additional HA programs were created for testing bimodal conditions with restricted bandwidth. Lesser amounts of amplification in the higher frequencies were achieved by turning down the gain in channels at frequencies above 2000 Hz (Program 2, BM2k), 1000 Hz (Program 3, BM1k) and 500 Hz (Program 4, BM500), respectively. REIG measurements were also obtained for each of these programs to document the reduced bandwidths. Figure 2 provides an example of the measures obtained from one of the participants. The NAL-RP target and the frequency responses for the four bandwidth conditions are shown. For this participant the match to target in the wideband condition was quite good. The three additional frequency responses on the graph illustrate the change in the HA bandwidth achieved in the HA. Note that among the 33 participants, data are included from eight participants included in a previous report (Neuman and Svirsky 2013). For those participants, the prescribed 2cc coupler gain for the wideband (NAL-RP) setting was calculated using average real-ear-to-coupler difference values and the match to target of the wideband and alternative bandwidths was verified in a 2 cc coupler using a weighted broadband noise signal (65 dB SPL).

A summary of the match to target as a function of the highest frequency matched for participants in each of the groups is shown in Table 3. In the CI>HA group it was possible to match to target at low and mid-frequencies. However, it was not possible to match gain at frequencies above 2kHz for 5 of the participants, or above 3kHz for an additional 5

participants. As a result, the “wideband” condition for these 10 participants is narrower than the wideband condition for the remaining 13 participants. In contrast, match to target within 10 dB was achieved at frequencies up to and including 4000 Hz for all 10 of the participants in the HA>CI group.

Materials and Protocol

Test materials were chosen to allow for the assessment of word recognition in sentences and word recognition in isolation (monosyllabic words). Both types of speech materials have been used in previous studies of speech recognition performance by bimodal listeners (Dorman and Gifford 2010). Each type of speech material may provide different information about the contribution of HA bandwidth to bimodal speech perception because the relative importance of various frequency bands in a speech signal is dependent on the speech material. The frequency importance function for sentences is weighted more heavily to lower frequencies than is the importance function for monosyllabic words (Studebaker et al. 1987).

Word recognition in sentences was assessed using the AzBio Sentence Test (+10 dB SNR, signal-to-noise ratio). Recordings of this test material consist of 33 lists of 20 sentences, with a multi-talker competing noise track. This material was specifically designed for use in the evaluation of speech recognition performance of CI users and is now commonly used for testing word recognition in sentences (in noise) because it is less likely to yield ceiling scores than recordings of easier sentence materials (Gifford et al. 2008). Recordings of 30 lists of monosyllabic CNC (consonant-nucleus-consonant) words created at the University of Melbourne and recorded in the United States were used to test word recognition in isolation (Skinner et al. 2006). Because there are 30 lists, for our purposes we call these test materials “CNC-30” to differentiate these recordings from other CNC recordings/materials. It has been suggested that these CNC-30 recordings are suitable for clinical research. When used as recommended, they provide 15 list pairs of equivalent difficulty (100 test words per list pair) and are of greater difficulty (on average scores are 22% lower) than the more commonly used CNC recordings and thus are less likely to result in ceiling scores (Skinner et al. 2006).

Thirty-three participants were tested using the AzBio sentences in noise (+10 dB SNR). Data from 8 of these subjects were included in our earlier report (Neuman and Svirsky 2013). Of the 33 participants, 23 were also tested using the CNC-30 word materials.

Data was obtained in two sessions: one session per test material. Order of testing was counterbalanced among subjects. In each session, six test conditions were assessed in random order: CI alone, HAWB alone (wideband fitting), Bimodal 500Hz (BM500), Bimodal 1000Hz (BM1k), Bimodal 2000Hz (BM2k), and Bimodal wideband (BMWB).

Before testing began, the participant was asked to balance the loudness between the CI and the HAWB. To balance loudness across HA and CI devices, the CI was set to the participant’s everyday program and volume, and the HA was set to the wideband setting. Running speech was presented at 65 dB SPL and the participant adjusted the volume control on the HA to match the loudness of the sound through the CI. All participants succeeded in

matching loudness. Once loudness balance was achieved for the wideband HA condition, no further adjustments were made to the HA volume when testing bimodal conditions with narrower bandwidths. It is possible that reducing the hearing aid bandwidth will also reduce the loudness of the amplified signal. It is difficult to exclude the possibility that matching the loudness between the CI and BM 500 might further improve the bimodal performance in the reduced bandwidth condition. However, by maintaining the volume control of the HA fixed, it is possible to compare the contribution of acoustic stimuli across bandwidths as the audibility of different frequency regions remains constant in each filtered condition. This same approach has been used in other filtering studies (e.g., Zhang et al. 2010; Sheffield and Gifford 2014).

All testing was carried out in a double-walled, double-room IAC (industrial Acoustics Company) test suite. The majority of the participants were tested in soundfield. Recordings of test materials (.wav files) were stored on a personal computer. The output of the computer was sent to an Echo-Layla 24 sound card, amplified (Crown D-75) and presented through an Audax HP080M0 loudspeaker. Presentation of the test stimuli was controlled using custom presentation software. Subjects sat at a distance of one meter from the loudspeaker (0° azimuth). Speech was presented at 65 dB SPL. Calibration was carried out daily (Larsen Davis 800 B sound level meter and 2559 microphone).

A number of participants were tested using calibrated direct-input testing in order to ensure that the non-test ear did not contribute to the measure of unimodal performance. For the participants who had good low and mid-frequency hearing in the non-implant ear, and for the participant with residual hearing in the implanted ear, calibrated direct-input testing was done in each of the test conditions. For persons with moderately-severe hearing loss in the non-implant ear, the ear was plugged using 3M E-A-R classic foam earplugs (St. Paul, MN). We then verified that the speech presented in soundfield (65 dB SPL) was not audible with the CI off and the non-implant ear plugged. If speech was audible when the non-implant ear was plugged, calibrated direct-input testing was done.

Data analysis

Differences in the effect of HA bandwidth on bimodal performance were determined on an individual basis, for descriptive purposes, using the 95% confidence interval tables developed for the AzBio sentence materials by Spahr et al. (2012) and for word lists by Carney and Schlauch (2007).

Before statistical analysis of speech recognition performance, speech recognition scores were converted to Rationalized Arcsine Units, RAU, (Studebaker 1985) in order to homogenize the variance of scores. This approach was used to address the few data points that were at floor or ceiling levels. Then, separate analyses were carried out for each group for each test material. Statistical analyses were performed using SAS 9.4 (SAS Institute Inc., Cary NC). In order to simultaneously model correlated test scores across multiple test conditions for each subject, the linear mixed effect model was utilized to quantify the relationship between speech recognition scores and conditions (best unimodal, BM500, BM1k, BM2k, and BMWB). The covariates listed below, as well as the corresponding interaction terms between each covariate and test condition, were adjusted in the mixed

effect model to determine if they had an influence on outcomes. The analysis procedure and the covariates that were used were exactly the same for the CI>HA and the HA>CI groups. Covariates were: age, gender, length of time that a HA had been used in the HA ear, side of implantation (left or right), length of experience with the CI, low-frequency PTA (LFPTA) in the HA ear (average of thresholds at 250 and 500 Hz), mid-frequency PTA (MFPTA) in the HA ear (average of thresholds at 1,000 and 2,000 Hz), PTA (average thresholds at 500, 1,000, and 2,000 Hz) and the slope of the unaided audiogram in the HA ear (operationalized as the difference between the mid-frequency PTA and the low-frequency PTA). In order to determine whether any of the bimodal conditions resulted in significant changes in speech recognition performance, planned comparisons were made between the best unimodal condition (that is, the CI condition for the CI>HA group, or the HA condition for the HA>CI group) and each one of the four bimodal test conditions (for each set of data analyzed). Comparisons were also made between the BMWB condition and the other three bimodal conditions, to determine whether restricting HA bandwidth affected bimodal performance. An adjustment was made to account for the fact that seven planned comparisons were made. A family-wise type I error of 0.05 was used, so the Bonferroni-corrected significance level was $0.05/7=0.0071$. All levels of significance for planned comparisons will be reported at the 0.05 level (after Bonferroni correction).

Results

Performance of individual participants as a function of test condition

Speech recognition scores for each speech material in each test condition are shown in Table 4 for participants with CI>HA. Scores on the AzBio test appear on the left side of the table. As can be seen in the table, CI-alone scores exceeded 50% for all but one participant. Bimodal scores are shown as a function of bandwidth. Scores in **bold** font indicate bimodal scores significantly higher than the CI alone scores [exceeding the 95% confidence interval based on a binomial distribution, (Spahr et al. 2012)]. Ten of 23 participants obtained significantly higher scores in bimodal conditions than in the CI-alone condition on the AzBio test material. Of those who showed such improvements, six participants obtained increased performance with the HA set to roll off frequencies above 500 Hz. For these participants, scores did not change significantly as the HA bandwidth was expanded to include higher frequencies. Four participants required wider bandwidths to obtain bimodal benefit: one participant needed at least the 1kHz bandwidth, two needed at least the 2kHz bandwidth, and one only received bimodal benefit in the WB condition. For the 13 remaining participants, bimodal scores did not differ significantly from the CI-alone score.

Speech recognition scores on the CNC-30 test material are shown in the right side of Table 4. Eleven of 15 participants had scores exceeding 50% with the CI. Scores with the HA ranged from 0% - 44%. Bimodal scores are shown as a function of HA bandwidth. Scores in **bold** indicate bimodal scores significantly higher than the CI alone scores [exceeding the 95% confidence interval based on a binomial distribution (Carney and Schlauch 2007)]. Five of 15 participants obtained significant improvements in bimodal conditions over CI-alone performance on CNC-30 words. Three participants obtained improvements in the BM500

condition and two required wider bandwidths (BM2k or BMWB). For the remaining 10 participants, bimodal scores did not differ significantly from the CI-alone condition.

Speech recognition scores in each test condition are shown in Table 5 for the HA better participants. As shown in the left side of the table, 10 participants were tested using the AzBio Sentence Test Materials in noise (+10 dB SNR). To determine how changing the HA bandwidth affects bimodal speech recognition performance, the score in each bimodal condition is compared with the HAWB condition (best unimodal performance). For 8 of the 10 participants, restricting the bandwidth of the HA caused significant decrements in bimodal performance (shown in red) relative to performance in the HAWB condition. For 7 of these subjects, the BMWB condition did not differ significantly from performance in the HAWB condition. One subject scored higher in the BMWB condition. For the remaining 2 subjects, there was no significant difference in performance among test conditions (HAWB and bimodal conditions).

As seen in the right portion of Table 5, eight participants in this HA better group were tested using the CNC-30 words. CI-alone scores were below 50% for six of the participants (range = 10% to 57%) and HAWB-alone scores were also below 50% for the same six participants (range = 23% to 75%). Five participants showed a significant increase (over HAWB-alone performance), again shown in **bold**. The BMWB yielding benefit differed among participants. For one participant, performance was significantly higher than the HAWB condition in all bimodal conditions. Several participants required mid-frequency information: one participant obtained significantly higher performance than HAWB for bimodal conditions BM1k and above, three of the participants required either the BM2k or the BMWB condition in order to obtain significant improvement over the HAWB-alone condition.

If the bimodal conditions were to be compared to the CI-alone condition (poorer unimodal condition), it is clear that the HA is contributing to bimodal performance. On the AzBio sentences in noise, higher scores would have been shown for many of the subjects for the BM500 condition and all in the BM 2k condition and BMWB condition than in the CI-alone condition. But this would overlook the fact that for six of the ten subjects these scores would be poorer than performance with the HA(WB) unimodal condition. On the CNC-30 test material, the differences in performance between the CI-alone and HAWB-alone conditions are smaller. Again, higher scores would have been shown for several of the subjects in the BM500 condition than in the CI alone condition, but for other subjects this only happened in the wider bandwidth conditions.

Linear Mixed effect modeling analysis: CI better group

A linear mixed effect modeling analysis of the performance on the AzBio sentence test in unimodal and bimodal conditions revealed a significant effect of test condition [$F(4, 86) = 8.25, p < .0001$]. Mean speech recognition scores (RAU) are shown in Figure 3a. Planned comparisons were carried out to determine (a) significant differences between the best unimodal condition (CI alone) and bimodal test conditions, and (b) significant differences between the BMWB condition and restricted bandwidth conditions (BM2k, BM1k and BM500). Scores were significantly higher than with the CI alone in each of the bimodal test

conditions ($p < 0.05$, after Bonferroni correction). Comparisons between the BMWB condition and the other bimodal conditions revealed that although performance in the BMWB condition was marginally higher, none of the paired comparisons between the narrower bandwidth conditions and the BMWB condition was significant ($p > 0.05$, after Bonferroni correction).

Of the demographic and audiometric covariates examined, the MFPTA and slope (MFPTA-LFPTA) were the only covariates that interacted significantly with speech recognition performance. The interaction between MFPTA and test condition is shown in Figure 3b. Differences between speech recognition scores (RAU) in each bimodal condition and the CI-alone condition are shown as a function of MFPTA (average of thresholds at 1kHz and 2kHz). Quartile 1 represents participants whose MFPTA is in the top 25% (lower MFPTA), Quartile 3 represents those in the 50 to 75th percentiles (higher MFPTA), and the Median represents those between the 25th and 50th percentile. Columns marked with an asterisk indicate significant increases in performance in the bimodal condition ($p < .05$ with Bonferroni correction). As can be seen, those with the best mid-frequency hearing (Quartile 1, 72.5 dB) obtained significant improvement in speech recognition (11.5 RAU) only in the BMWB condition. Subjects with MFPTA at the median (82.5 dB) or third quartile level (95 dB) obtained significant improvement in all bimodal conditions, including those with the restricted bandwidths.

The planned comparisons between the BMWB and each restricted bimodal condition revealed that for the participants with better mid-frequency PTA (Quartile 1, 72.5 dB), AzBio performance in the BMWB condition was significantly higher than either the BM500 or BM1k condition (≈ 9 RAU), but did not differ significantly from the BM2k condition after the Bonferroni correction (≈ 7 RAU). For those with greater mid-frequency hearing loss (MFPTA 82.5 dB), performance in the BMWB condition did not differ significantly from any of the other BM conditions.

The interaction between the slope of the audiogram and condition was also significant [$F(4, 82) = 4.51, p = 0.0024$]. Recall that slope is the difference between the mid-frequency (1000 and 2000 Hz) and low-frequency (250, 500 Hz) PTAs. The effect of this interaction is shown in Figure 3c. Differences between performance in each bimodal condition and the CI-alone condition are shown as a function of slope. Again, columns marked with an asterisk indicate significant increases in performance in the bimodal condition ($p < .05$ with Bonferroni correction). For subjects with steeper audiogram slopes ($Q3 = 32.5$ dB) there was significant improvement in performance in all bimodal conditions, and the amount of that improvement was roughly similar across conditions (from 10.54 RAU for BM500 to 13.52 RAU for BMWB). In contrast, subjects with shallower slopes (Quartile 1 = 7.5 dB) showed significant improvement only in the BMWB condition (10.29 RAU), not in the BM500, BM1k, or BM2k conditions. This is consistent with better hearing in the low frequencies being more useful for improving speech recognition in the bimodal conditions for those with more steeply sloping hearing loss (more elevated thresholds in the mid and high-frequency regions). In contrast, those with an audiogram having a flatter configuration required a wider hearing aid bandwidth in order to obtain substantially higher scores in the bimodal condition than in the best unimodal condition.

The comparison between the BMWB and other bimodal conditions reveals that for those with flatter audiometric configuration (Quartile 1, 7.5 dB), the BMWB condition was significantly higher than either the BM500 or BM1k conditions (8–9 RAU higher), but was not significantly different than the BM2k condition. For those with more steeply sloping audiometric configurations, the BMWB did not differ significantly from the restricted bandwidth conditions.

The linear mixed effect modeling analysis of the performance on the CNC-30 test material revealed that performance did not differ significantly as a function of test condition (CI alone, BM500, BM1k, BM2k, BMWB) [$F(4,54) = 2.10$, $p > 0.05$]. Mean speech recognition scores (RAU) are shown in Figure 4. None of the covariates interacted significantly with test condition.

Linear Mixed effect modeling analysis: HA better group

The linear mixed effect modeling analysis of the performance on the AzBio sentence test revealed a significant effect of test condition [$F(4,36) = 11.12$, $p < .0001$]. Mean speech recognition scores (RAU) as a function of test condition are shown in Figure 5a. Recall that for these subjects, the HAWB condition is the best unimodal condition. Bimodal performance is compared to the HAWB performance to determine changes from the best unimodal condition. Planned comparisons of means revealed that speech recognition was significantly poorer in the BM500 and the BM1k conditions than in the HAWB condition ($p < .05$, after Bonferroni correction). Mean performance in the BMWB condition and in the BM2k condition did not differ significantly from performance in the HAWB condition ($p > .05$, after Bonferroni correction). In short, there was a significant decrement in bimodal performance (from the unimodal HAWB condition) as the bandwidth of the HA was reduced.

None of the demographic covariates interacted significantly with speech recognition performance. Both the LFPTA and PTA interacted with test condition. The significant interaction between the LFPTA and condition [$F(4,32) = 6.41$, $p = 0.0007$] is shown in Figure 5b. Differences between performance in each bimodal condition and the HAWB condition are shown as a function of LFPTA. The interaction revealed that those with better low-frequency hearing (Quartile 1 = 35 dB) had smaller decreases in performance in the BM500 and BM1k bandwidths than those with more low-frequency hearing loss. The difference in performance between the BM2k and HAWB, or BMWB and HAWB was more similar across different LFPTAs. This interaction indicates that those with poorer thresholds at 250 and 500 Hz are unable to benefit as much from amplified low-frequency information than those with better low-frequency hearing. The planned comparisons between the BMWB condition and each of the restricted bandwidths revealed that performance in the wideband condition was significantly higher than in the BM1k or in the BM500 condition for each of the LFPTA quartiles. For those with the best LFPTA (Quartile 1), performance in the BMWB and BM2k condition did not differ significantly. For those with poorer low-frequency hearing, the wideband condition was significantly better than the BMB2k condition.

The interaction between LFPTA and the contrasts among the bimodal conditions is also consistent with the pattern that those with better low-frequency hearing show a smaller difference between the BMWB condition and each of the other bimodal conditions, i.e., the benefit from the HA is primarily from amplification of the low frequencies. As the LFPTA increases, the difference between performance in the BMWB and each of the other bandwidths increases. In all cases, the wider the bandwidth the better the performance.

The interaction between PTA and condition was also significant ($F(4,32) = 3.84, p < 0.0116$). The interaction is illustrated in Figure 5c. Differences between performance in each bimodal condition and the HAWB condition are shown as a function of PTA. The pattern of the interaction is very similar as the pattern seen for the LFPTA interaction. The decrease in performance through reduction of the bandwidth was less for those with better hearing in the non-implant ear than for those with more hearing loss.

The linear mixed effect modeling analysis of the performance on the CNC-30 test material revealed a significant effect of test condition [$F(4, 28) = 6.92, p < .0005$]. Mean speech recognition scores (RAU) as a function of test condition are shown in Figure 6a. Planned comparisons between each of the bimodal conditions and the HAWB-alone condition revealed that performance did not differ significantly ($p > .05$, after Bonferroni correction) between the BM500 and the HAWB condition or between the BM1k condition and the HAWB condition. However performance was significantly better ($p < .05$, after Bonferroni correction) in the BM2k condition than in the HAWB condition and was also significantly better in the BMWB condition than in the HAWB condition. This is consistent with a *contribution of information from the CI* in combination with the acoustic information provided by the HAWB. Comparisons between the BMWB condition and each of the narrower bandwidths revealed that performance was significantly better in the BMWB than BM500 condition ($p < 0.05$, after Bonferroni correction), but neither the BM1k nor the BM2k conditions differed significantly from the BMWB condition.

The interaction between LFPTA and condition was significant [$F(4,24) = 4.52, p = 0.0073$]. The effect of this interaction is shown in Figure 6b. As can be seen in the figure, for those with good low-frequency hearing ($Q1 = 26.5$ dB) the BM1k condition was the narrowest bandwidth yielding significant improvement in the bimodal condition when compared to the HAWB condition, and further improvements occurred as the bandwidth increased. For those with moderate LFPTA (median = 41.25 dB) the BM2k condition was the narrowest bandwidth yielding significant bimodal condition. This is consistent with useful information from the CI being combined with low and mid-frequency information being provided through the HA(WB). For those with more loss in the low frequencies (Quartile 3 = 55 dB), there was a significant decrease in performance in the BM500 Hz condition, and BM1k, BM2k and BMWB conditions did not differ significantly from the HAWB condition. The planned comparisons between the BMWB condition and each of the restricted bandwidths revealed that performance in the BM1k and BM2k conditions did not differ significantly from the BMWB condition for any of the LFPTA groups. Performance in the BM500 condition did not differ significantly from the BMWB condition for those with the best low-frequency thresholds (Quartile 1), but was significantly poorer than the BMWB condition for those with more low frequency hearing loss.

Discussion

In this study, we set out to determine the influence of HA bandwidth on the bimodal speech perception of individuals who use a CI in one ear and a HA in the contralateral ear. A second goal was to identify demographic and/or audiometric characteristics that would affect the appropriate bandwidth yielding an increase in bimodal (over unimodal) scores.

Like any other study, ours has several limitations. By design, the same HA and prescriptive procedure were used for all participants. However, the HA frequency response likely differed from the response of the participant's personal HA. Because all testing was done acutely, subjects did not have the opportunity to acclimate to the wideband HA fitting or to using the restricted bandwidth settings. Other than making changes to the volume control to match the loudness of the (wideband) HA to the loudness of the CI, no individualized changes to the frequency response were carried out. The NAL-RP prescriptive target was used for the HAWB setting. Since the NAL-RP prescription for "average conversational speech level" is similar to the NAL-NL1 prescription, the results of this study can be compared directly to other studies which used either the NAL-RP target (Zhang et al. 2010) or the NAL-NL1 prescriptive procedure (Sheffield and Gifford 2014). Admittedly, this target differs from the current NAL-NL2 prescriptive procedure with regard to the amount of amplification provided at different frequencies. Specifically, the NAL-NL2 prescription would generally provide more gain in the low-frequency region and less gain in the mid-frequency region (Keidser et al. 2011). Use of a different prescriptive procedure than the one we used might have influenced results in any given condition, but it is unlikely to have affected relative bimodal performance as a function of bandwidth. In fact, a recent study of performance by bimodal patients with HAs fit using the NAL-NL2 prescription showed better performance with the newer prescription in the HA-alone condition than with the participant's own HA, but no improvement in the bimodal condition (English et al. 2016).

Another limitation is that the test protocol was confined to assessment of speech recognition performance with speech stimuli presented from directly in front of the subjects. No attempt was made to test the effect of bandwidth on tasks that would reveal benefits from access to bilateral cues. Recent research has shown that wideband amplification or access to acoustic high frequencies using non-linear frequency compression is superior to a restricted bandwidth on a localization task (Davidson et al. 2015). Tests of bilateral function would have served to highlight potential real-world benefits from access to sound using both devices.

On the other hand, this study has some potentially interesting differences from some of the earlier studies. First, a commercial HA was used to study the effect of HA bandwidth. The software within the HA was used to set the upper frequency of the HA bandwidth. This is the sort of control that an audiologist will have in clinical practice. Using an actual hearing aid (as opposed to simulating a hearing aid with computer-based filtered speech) has the advantage of incorporating the bandpass characteristics and frequency range typical of the devices bimodal patients will be using. The slope of the filters of the HA are not as steep as those typically used in a study with filtered speech, but should reveal the results of bandwidth modifications obtainable using a real hearing aid. Another important difference

has to do with the participants' audiometric configuration. While previous studies focused primarily on listeners with relatively good low-frequency hearing and steeply sloping hearing loss in the non-implanted ear (e.g., Zhang et al. 2010, Sheffield and Gifford 2014), by design this research included participants with different degrees and configurations of hearing loss. Some of these participants had sufficient residual hearing at mid (1000, 2000 Hz) and higher frequencies (3000 and 4000 Hz) to achieve "effective audibility" at those frequencies. Inclusion of these participants allowed for the possibility to determine how mid- and high-frequency acoustic information might contribute to bimodal performance.

The approach taken in analyzing data was to compare speech recognition performance in each bimodal condition to the performance in the best unimodal condition. As the criteria for cochlear implantation change, candidacy may be considered based on degree of hearing loss and aided speech recognition performance in each ear. This opens the possibility of persons who are candidates for a cochlear implant in one ear, but can obtain substantial benefit from the hearing aid in the contralateral ear- in some cases, more than they obtain from the CI. Of the 33 participants, 10 could be classified as actually obtaining better performance with the HA than with the CI for word recognition in sentences. The question addressed was how the manipulation of the HA bandwidth would affect bimodal performance in both groups: the more traditional group of bimodal CI users who understand speech better with the CI than with the HA (CI>HA) and the less typical group of bimodal CI users who actually understand speech better with the HA than with the CI (HA>CI).

For the CI>HA group, mean performance on the AzBio sentences in noise was significantly higher than CI-alone performance *in each* of the bimodal conditions. This finding is consistent with previous studies that emphasize that bimodal benefit can be obtained when low-frequency acoustic information provided by the HA is provided to complement the information obtained from the CI (Ching et al. 2004; Mok et al. 2006; Zhang et al. 2010; Sheffield and Gifford 2014). But there were individual differences in how the bandwidth contributed to increased bimodal performance. Examination of the covariates that significantly affected AzBio scores yielded two main results indicating that the slope of the audiogram and the degree of mid-frequency hearing loss both affect how hearing aid bandwidth will influence bimodal speech recognition performance. With a flat configuration of hearing loss and better mid-frequency hearing, only the wideband HA yields improvement in AZBio performance (over CI alone performance). Those with greater mid-frequency hearing loss and sloping hearing loss obtained significant increases in performance over CI-alone performance in all restricted bandwidth conditions, as well as in the wideband condition. For our participants, there was no benefit to limiting the bandwidth. There was a trend for the bimodal scores to continue to increase with increasing bandwidth, even when there was significant improvement with the restricted bandwidth. Zhang et al (2014) provided direct evidence that those with dead regions on the cochlea obtained better bimodal performance when amplification was restricted to frequencies below the dead region, whereas those without dead regions obtained higher bimodal performance with a wideband HA fitting. Based on our results, it appears that either none of the participants in the current study had dead regions on the cochlea (this was not assessed directly), or that for participants with profound hearing loss at high frequencies where dead regions might have been present that the obtained wideband fitting did not extend to dead regions.

The results of the analysis of interaction effects are consistent with hearing aid research that has shown that the ability of persons with hearing loss to extract information from an amplified signal is dependent on his/her degree and configuration of hearing loss. In particular, Hornsby et al. (2011) report that: (1) those with flatter hearing loss configurations are less able to obtain benefit from low-pass filtered speech than those with more steeply sloping hearing loss, (2) those with flat audiometric configuration obtain benefit from access to a wideband speech signal, (3) a wide bandwidth HA either provided benefit, or did not decrease performance for a wide range of hearing levels and configurations. Therefore, it would appear that the same considerations for fitting the hearing aid for patients who do not use a cochlear implant may be relevant to fitting the hearing aid for bimodal patients.

As the degree of hearing loss increases, hearing desensitization limits the information that can be used from an amplified signal—even when the signal has been made audible (Ching et al. 1998; Hogan and Turner 1998; Hornsby et al. 2011; Hornsby and Ricketts 2006). Ching and colleagues (Ching et al. 1998; Ching et al. 2011) provided evidence that once hearing loss exceeds 65 dB HL, the listener can extract only half of the audible information (as compared to a listener with normal hearing). As thresholds increase, the amount of information that can be extracted from audible speech decreases. With thresholds of 90 dB HL, effective audibility is dramatically reduced and may not contribute in a meaningful way to speech intelligibility.

The participants with HA>CI performance are less typical bimodal users, but are representative of those who receive a unilateral implant because the hearing in the implanted ear meet implantation criteria. This group had good performance on the sentences in noise with the HAWB (mean = 72.7 RAU) and relatively poor performance with the CI alone (mean score = 28.7 RAU). For these participants, it was important to use the best unimodal condition as the reference condition. Had the CI been used as the reference condition, very large “bimodal” benefits would have been observed what would have simply represented the superior performance in the HA-only condition rather than true bimodal benefit. Only the BMWB condition yielded performance similar to performance in the HAWB condition. Bimodal performance was negatively affected by reducing the bandwidth of the HA. The size of the decrement in performance was dependent on the degree and configuration of hearing loss. Those with better low-frequency hearing were less affected by reducing the bandwidth. But, clearly reducing the bandwidth is contraindicated.

While adding the signal from the CI to the information obtained through the HAWB did not lead to significant changes in performance on the AzBio sentences in the HA>CI group, the pattern of performance seen on the CNC-30 test material does provide evidence of bimodal integration of the HA and the CI signal. Five of eight of the HA>CI participants obtained significantly higher scores on the CNC-30 test material in bimodal conditions than in the HAWB condition. Mean performance on the CNC-30 was significantly higher than HAWB condition in both the BM2k and BMWB conditions. This demonstrates that the CI is contributing high frequency information that is not readily available to the listener when using the HAWB alone, and that the listener is able to integrate the information from both devices. The analysis of the interaction between LFPTA and condition shows that those with good low-frequency hearing obtained better bimodal performance on the CNC test material

with the BM1kHz setting than with the HAWB alone, and bimodal performance increased with increasing bandwidth. Those with low-frequency thresholds in the moderate range (≈ 40 dB HL) obtained better performance in the BM2k and BMWB condition than with the HAWB alone. Again, this supports provision of amplification at all frequencies where effective audibility is possible.

It is noteworthy that among those with HA>CI scores, mean performance with the CI on each of the test materials was poorer for these participants than for those with CI>HA performance (28.7 RAU vs. 67 RAU on the AzBio test in noise and 28.6 RAU vs. 53.7 RAU on the CNC-30 materials). Others have reported poorer unilateral CI scores in unilateral CI recipients with better hearing in the non-implanted ear (Plant, McDermott, et al. 2016). It is possible that these listeners who have better speech recognition with the HA than the CI are not accustomed to using the CI alone (and thus obtain relatively poor performance in the unimodal CI condition). Auditory training focused on listening with the CI alone might be helpful for these listeners (Zhang et al. 2012). Alternatively, increasing the lower cutoff frequency of the CI might reduce overlap between the HA and the CI and lead to better performance (Fowler et al. 2016).

Participants in the study were all experienced bimodal users who reported use of both devices on a daily basis. Yet, not all of the participants obtained better performance in bimodal conditions than in the best unimodal condition on the speech recognition tasks used to assess speech recognition performance. It is therefore important for the clinician to obtain input from the bimodal user about perceived benefit from using both devices in daily life (Neuman et al., 2017).

It is important to test performance in each unimodal condition and in bimodal listening conditions in order to determine the usefulness of each device separately and in combination. Decreased performance in the bimodal condition would identify interference and would necessitate investigation of how each of the devices could be adjusted (e.g., adjustment to the HA bandwidth or to the frequency range assignment in the CI processor). As a practical matter, testing of all three listening conditions and the ability to coordinate fittings of each device is less likely to occur if the bimodal user is treated by two different clinicians, one responsible for care of the CI and another for the care of the HA.

Conclusions

Taken together, our results support fitting the HA for all bimodal patients in a way that will provide amplification at all frequencies where effective audibility is possible. In both the CI>HA group and in the HA>CI group, the pattern of bimodal performance as a function of the HA bandwidth was found to be consistent with the degree and configuration of hearing loss.

Fitting the hearing aid for the bimodal patient should begin with a well-established prescriptive target that takes effective audibility into account. For patients with good low-frequency thresholds and steeply-sloping audiometric configuration, a hearing aid providing amplification primarily to the low frequencies in combination with the contralateral CI can

result in increased bimodal performance. For those patients with more residual hearing, amplification should be provided at all frequencies where effective audibility is possible. This approach is likely to yield increased bimodal performance.

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References

- Armstrong M, Pegg P, James C, et al. (1997). Speech perception in noise with implant and hearing aid. *Am J Otol*, 18 (Suppl. 6), S140–S141. [PubMed: 9391635]
- Arndt S, Laszig R, Aschendorff A, et al. (2017). Cochlear implant treatment of patients with single-sided deafness or asymmetric hearing loss. *HNO*, 1–11. [PubMed: 27695891]
- Brown CA, and Bacon SP (2010). Fundamental frequency and speech recognition in noise, *Hear. Res.* 266, 52–59. [PubMed: 19748564]
- Byrne D, Dillon H, Ching T, et al. (2001). NAL-NL1 procedure for fitting nonlinear hearing aids: characteristics and comparisons with other procedures. *J Am Acad Audiol*, 12, 37–51. [PubMed: 11214977]
- Byrne D, Parkinson A, Newall P (1990). Hearing aid gain and frequency response requirements for the severely/profoundly hearing impaired. *Ear Hear*, 11, 40–49. [PubMed: 2307302]
- Byrne D, Parkinson A, Newall P (1991). Modified Hearing-Aid Selection Procedures for Severe Profound Hearing Losses In Studebaker GA, Bess FH, Beck L (Eds.), *Vanderbilt Hearing Aid Report II* (pp. 295–300). Parkton, MD: York Press.
- Cadieux JH, Firszt JB, Reeder RM (2013). Cochlear implantation in nontraditional candidates: preliminary results in adolescents with asymmetric hearing loss. *Otol Neurotol*, 34, 408–415. [PubMed: 23222962]
- Carney E, Schlauch RS (2007). Critical difference table for word recognition testing derived using computer simulation. *J Speech Lang Hear Res*, 50, 1203–1209. [PubMed: 17905906]
- Ching TY, Dillon H, Byrne D (1998). Speech recognition of hearing-impaired listeners: predictions from audibility and the limited role of high-frequency amplification. *J Acoust Soc Am*, 103, 1128–1140. [PubMed: 9479766]
- Ching TY, Dillon H, Lockhart F, et al. (2011). Audibility and speech intelligibility revisited: Implications for amplification. In Dau T, Dalsgaard ML Jepsen, & Poulsen T (Ed.), *Speech*

perception and auditory disorders. 3rd International Symposium on Auditory and Audiological Research (pp. 11–19). Denmark: The Danavox Jubilee Foundation.

- Ching TY, Incerti P, Hill M (2004). Binaural benefits for adults who use hearing aids and cochlear implants in opposite ears. *Ear Hear*, 25, 9–21. [PubMed: 14770014]
- Davidson LS, Firszt JB, Brenner C, et al. (2015). Evaluation of hearing aid frequency response fittings in pediatric and young adult bimodal recipients. *J Am Acad Audiol*, 26, 393–407. [PubMed: 25879243]
- Dorman MF, Gifford RH (2010). Combining acoustic and electric stimulation in the service of speech recognition. *Int J Audiol*, 49, 912–919. [PubMed: 20874053]
- English R, Plant K, Maciejczyk M, et al. (2016). Fitting recommendations and clinical benefit associated with use of the NAL-NL2 hearing-aid prescription in Nucleus cochlear implant recipients. *Int J Audiol*, 55 Suppl 2, S45–50. [PubMed: 26853233]
- Farinetti A, Roman S, Mancini J, et al. (2015). Quality of life in bimodal hearing users (unilateral cochlear implants and contralateral hearing aids). *Eur Arch Otorhinolaryngol*, 272, 3209–3215. [PubMed: 25373837]
- Fielden CA, Kitterick PT (2016). Contralateral acoustic hearing aid use in adult unilateral cochlear implant recipients: Current provision, practice, and clinical experience in the UK. *Cochlear Implants Int*, 17, 132–145. [PubMed: 27078521]
- Firszt JB (2008). Restoring hearing symmetry with two cochlear implants or one cochlear implant and a contralateral hearing aid. *The Journal of Rehabilitation Research and Development*, 45, 749–768. [PubMed: 18816424]
- Firszt JB, Holden LK, Reeder RM, et al. (2012). Cochlear implantation in adults with asymmetric hearing loss. *Ear Hear*, 33, 521–533. [PubMed: 22441359]
- Flynn MC, Schmidtke T (2004). Benefits of bimodal stimulation for adults with a cochlear implant In *International Congress Series* (pp. 227–230): Elsevier.
- Folstein MF, Folstein SE, McHugh PR (1975). “Mini-mental state”. A practical method for grading the cognitive state of patients for the clinician. *J Psychiatr Res*, 12, 189–198. [PubMed: 1202204]
- Fowler JR, Eggleston JL, Reavis KM, et al. (2016). Effects of Removing Low-Frequency Electric Information on Speech Perception With Bimodal Hearing. *J Speech Lang Hear Res*, 59, 99–109. [PubMed: 26535803]
- Gifford RH, Dorman MF, McKarns SA, et al. (2007). Combined electric and contralateral acoustic hearing: word and sentence recognition with bimodal hearing. *J. Speech. Lang. Hear. Res*, 50, 835–843. [PubMed: 17675589]
- Gifford RH, Dorman MF, Shallop JK, et al. (2010). Evidence for the expansion of adult cochlear implant candidacy. *Ear Hear*, 31, 186–194. [PubMed: 20071994]
- Gifford RH, Dorman MF, Sheffield SW, et al. (2014). Availability of binaural cues for bilateral implant recipients and bimodal listeners with and without preserved hearing in the implanted ear. *Audiol Neurotol*, 19, 57–71. [PubMed: 24356514]
- Gifford RH, Shallop JK, Peterson AM (2008). Speech recognition materials and ceiling effects: considerations for cochlear implant programs. *Audiol Neurotol*, 13, 193–205. [PubMed: 18212519]
- Hogan CA, Turner CW (1998). High-frequency audibility: benefits for hearing-impaired listeners. *J Acoust Soc Am*, 104, 432–441. [PubMed: 9670535]
- Hornsby BW, Johnson EE, Picou E (2011). Effects of degree and configuration of hearing loss on the contribution of high- and low-frequency speech information to bilateral speech understanding. *Ear Hear*, 32, 543–555. [PubMed: 21336138]
- Hornsby BW, Ricketts TA (2006). The effects of hearing loss on the contribution of high- and low-frequency speech information to speech understanding. II. Sloping hearing loss. *J Acoust Soc Am*, 119, 1752–1763. [PubMed: 16583917]
- Keidser G, Dillon H, Flax M, et al. (2011). The NAL-NL2 Prescription Procedure. *Audiol Res*, 1, e24. [PubMed: 26557309]
- Kong YY, Stickney GS, and Zeng F-G (2005). Speech and melody recognition in binaurally combined acoustic and electric hearing. *J. Acoust. Soc. Am.* 117(3), 1351–1361. [PubMed: 15807023]

- Kong YY, and Carlyon RP (2007). Improved speech recognition in noise in simulated binaurally combined acoustic and electric stimulation, *J. Acoust. Soc. Am.* 121(6), 3717–3727. [PubMed: 17552722]
- Leigh JR, Moran M, Hollow R, et al. (2016). Evidence-based guidelines for recommending cochlear implantation for postlingually deafened adults. *Int J Audiol*, 55 Suppl 2, S3–8.
- Messersmith JJ, Jorgensen LE, Hagg JA (2015). Reduction in High-Frequency Hearing Aid Gain Can Improve Performance in Patients With Contralateral Cochlear Implant: A Pilot Study. *Am J Audiol*, 24, 462–468. [PubMed: 26650016]
- Mok M, Grayden D, Dowell RC, et al. (2006). Speech perception for adults who use hearing aids in conjunction with cochlear implants in opposite ears. *J. Speech. Lang. Hear. Res.* 49, 338–351. [PubMed: 16671848]
- Morera C, Cavalle L, Manrique M, et al. (2012). Contralateral hearing aid use in cochlear implanted patients: multicenter study of bimodal benefit. *Acta Otolaryngol*, 132, 1084–1094. [PubMed: 22667256]
- Morera C, Manrique M, Ramos A, et al. (2005). Advantages of binaural hearing provided through bimodal stimulation via a cochlear implant and a conventional hearing aid: a 6-month comparative study. *Acta Otolaryngol*, 125, 596–606. [PubMed: 16076708]
- Neuman AC, Svirsky MA (2013). Effect of hearing aid bandwidth on speech recognition performance of listeners using a cochlear implant and contralateral hearing aid (bimodal hearing). *Ear Hear*, 34, 553–561. [PubMed: 23632973]
- Neuman AC, Waltzman SB, Shapiro WH, Neukam JD, Zeman AM, & Svirsky MA (2017). Self-reported usage, functional benefit, and audiologic characteristics of cochlear implant patients who use a contralateral hearing aid. *Trends in hearing*, 21, 2331216517699530.
- Offeciers E, Morera C, Muller J, et al. (2005). International consensus on bilateral cochlear implants and bimodal stimulation. *Acta Otolaryngol*, 125, 918–919. [PubMed: 16109670]
- Plant K, McDermott H, van Hoesel R, et al. (2016). Factors Predicting Postoperative Unilateral and Bilateral Speech Recognition in Adult Cochlear Implant Recipients with Acoustic Hearing. *Ear Hear*, 37, 153–163. [PubMed: 26462170]
- Plant K, Van Hoesel R, McDermott H, et al. (2016). Influence of contralateral acoustic hearing on adult bimodal outcomes after cochlear implantation. *Int J Audiol*, 55, 472–482. [PubMed: 27216386]
- Potts LG, Skinner MW, Litovsky RA, et al. (2009). Recognition and localization of speech by adult cochlear implant recipients wearing a digital hearing aid in the nonimplanted ear (bimodal hearing). *J Am Acad Audiol*, 20, 353–373. [PubMed: 19594084]
- Qin MK, and Oxenham AJ (2005). Effects of envelope-vocoder processing on F0. discrimination and concurrent-vowel identification, *Ear Hear*. 26, 451–460. [PubMed: 16230895]
- Qin MK, and Oxenham AJ (2006). Effects of introducing unprocessed low-frequency information on the reception of envelope-vocoder processed speech, *J. Acoust. Soc. Am.* 119(4), 2417–2426. [PubMed: 16642854]
- Sanhueza I, Manrique R, Huarte A, et al. (2016). Bimodal Stimulation with Cochlear Implant and Hearing Aid in Cases of Highly Asymmetrical Hearing Loss. *J Int Adv Otol*, 12, 16–22. [PubMed: 27340977]
- Schafer EC, Amlani AM, Paiva D, et al. (2011). A meta-analysis to compare speech recognition in noise with bilateral cochlear implants and bimodal stimulation. *Int J Audiol*, 50, 871–880. [PubMed: 22103439]
- Schafer EC, Amlani AM, Seibold A, et al. (2007). A meta-analytic comparison of binaural benefits between bilateral cochlear implants and bimodal stimulation. *J Am Acad Audiol*, 18, 760–776. [PubMed: 18354885]
- Scherf FW, Arnold LP (2014). Exploring the clinical approach to the bimodal fitting of hearing aids and cochlear implants: results of an international survey. *Acta Otolaryngol*, 134, 1151–1157. [PubMed: 25315914]
- Sheffield BM, Zeng FG (2012). The relative phonetic contributions of a cochlear implant and residual acoustic hearing to bimodal speech perception. *J Acoust Soc Am*, 131, 518–530. [PubMed: 22280613]

- Sheffield SW, Gifford RH (2014). The benefits of bimodal hearing: effect of frequency region and acoustic bandwidth. *Audiol Neurotol*, 19, 151–163. [PubMed: 24556850]
- Siburt HW, Holmes AE (2015). Bimodal Programming: A Survey of Current Clinical Practice. *Am J Audiol*, 24, 243–249. [PubMed: 25907807]
- Skinner MW, Holden LK, Fourakis MS, et al. (2006). Evaluation of equivalency in two recordings of monosyllabic words. *J Am Acad Audiol*, 17, 350–366. [PubMed: 16796301]
- Spahr AJ, Dorman MF, Litvak LM, et al. (2012). Development and validation of the AzBio sentence lists. *Ear Hear*, 33, 112–117. [PubMed: 21829134]
- Spitzer S, Liss J, Spahr T, Dorman M, Lansford K, (2009). The use of fundamental frequency for lexical segmentation in listeners with cochlear implants. *J. Acoust. Soc. Am.* 125, EL236e41. [PubMed: 19507928]
- Studebaker GA (1985). A “rationalized” arcsine transform. *J Speech Hear Res*, 28, 455–462. [PubMed: 4046587]
- Studebaker GA, Pavlovic CV, Sherbecoe RL (1987). A frequency importance function for continuous discourse. *J Acoust Soc Am*, 81, 1130–1138. [PubMed: 3571730]
- Turner CW, Gantz BJ, Vidal C, Behrens A, and Henry BA (2004). Speech recognition in noise for cochlear implant listeners: Benefits of residual acoustic hearing, *J. Acoust. Soc. Am.* 115(4), 1729–1735. [PubMed: 15101651]
- Van Loon MC, Smits C, Smit CF, et al. (2017). Cochlear Implantation in Adults With Asymmetric Hearing Loss: Benefits of Bimodal Stimulation. *Otol Neurotol*, 38, e100–e106. [PubMed: 28441230]
- Vermeire K, Van de Heyning P (2009). Binaural hearing after cochlear implantation in subjects with unilateral sensorineural deafness and tinnitus. *Audiol. Neurotol*, 14, 163–171. [PubMed: 19005250]
- Zhang T, Dorman MF, Fu QJ, et al. (2012). Auditory training in patients with unilateral cochlear implant and contralateral acoustic stimulation. *Ear Hear*, 33, e70–79. [PubMed: 22622705]
- Zhang T, Dorman MF, Gifford R, et al. (2014). Cochlear dead regions constrain the benefit of combining acoustic stimulation with electric stimulation. *Ear Hear*, 35, 410–417. [PubMed: 24950254]
- Zhang T, Dorman MF, Spahr AJ (2010). Information from the voice fundamental frequency (F0) region accounts for the majority of the benefit when acoustic stimulation is added to electric stimulation. *Ear Hear*, 31, 63–69. [PubMed: 20050394]

Figure 1.

Figure 1a. Pure tone thresholds (dB HL) of participants in the CI>HA group (n=23).

Figure 1b. Pure tone thresholds (dB HL) of participants in the HA>CI group (n=10).

Figure 2.

Real ear insertion gain measures from one of the participants (ISTS signal, 65 dB input).

Responses for the wideband (HAWB) and each of the narrower bandwidths are shown: 2kHz (HA2kHz), 1kHz (HA1kHz) and 500 Hz (HA.5kHz) are shown. The NAL-RP target is shown as the solid grey line.

CI > HA group (N=23)
AzBio Sentences (+10 dB SNR)

Figure 3.

Figure 3a. Mean scores (RAU) on the AzBio sentences (+10 dB SNR) as a function of test condition for CI>HA group. Error bars represent standard error of the mean. Asterisks indicate bimodal scores significantly higher than with CI-alone ($p < .05$, after Bonferroni correction).

Figure 3b. This panel shows the difference between bimodal speech recognition scores for each bandwidth and the CI-alone score on the AzBio sentences (+10 dB SNR) for the CI>HA group. It illustrates the interaction between bandwidth (indicated by bars of different

colors) and mid-frequency pure tone average (indicated by three different groups of bars: Quartile 1, Median, and Quartile 3) on bimodal performance. The error bars represent the standard error. Asterisks indicate bimodal conditions yielding significantly higher performance than with CI alone ($p < .05$, after Bonferroni correction).

Figure 3c. This panel shows the difference between bimodal speech recognition scores for each bandwidth and the CI-alone score. The interaction between bandwidth and slope of the audiogram on bimodal speech recognition is illustrated. The error bars represent the standard error. Asterisks indicate bimodal conditions yielding significantly higher performance than with CI alone ($p < .05$, after Bonferroni correction).

Figure 4.

Mean scores (RAU) on the CNC-30 test material as a function of test condition for CI>HA group. Error bars represent standard error of the mean.

Figure 5.

Figure 5a. Mean scores (RAU) on the AzBio sentence test (+10 dB SNR) as a function of test condition for HA>CI group. Error bars represent standard error of the mean. Asterisks indicate bimodal conditions with *significantly poorer performance* than with HAWB alone ($p<.05$, after Bonferroni correction).

Figure 5b. This panel shows the difference between bimodal performance on the AzBio sentences (+10 dB SNR) and the HAWB-alone score, for the HA>CI group. The interaction between low-frequency pure tone average (indicated by three groups of bars: Quartile 1,

Median, and Quartile 3) and bandwidth (indicated by bars of different color) on bimodal speech recognition is illustrated. The error bars represent standard error of the mean. Asterisks indicate bimodal conditions with *significantly poorer performance* than with HAWB alone ($p < .05$, after Bonferroni correction).

Figure 5c. This panel shows the difference between bimodal performance on the AzBio sentences (+10 dB SNR) and the HAWB-alone score for the HA>CI group. The interaction between pure tone average (indicated by three groups of bars: Quartile 1, Median, and Quartile 3) and bandwidth (indicated by bars of different color) on bimodal speech recognition is illustrated. The error bars represent standard error of the mean. Asterisks indicate bimodal conditions with *significantly poorer performance* than with HAWB alone ($p < .05$, after Bonferroni correction).

Figure 6.

Figure 6a. Mean scores (RAU) on the CNC-30 test material as a function of test condition for HA>CI group. Error bars represent standard error of the mean. Asterisks indicate conditions showing significant Improvement over HAWB-alone performance ($p<.05$, after Bonferroni correction).

Figure 6b. This panel shows the difference between bimodal performance on CNC-30 words and the HAWB-alone score for the HA>CI group. The interaction between low-frequency pure tone average (indicated by three groups of bars: Quartile 1, Median, and Quartile 3) and

bandwidth (indicated by bars of different color) on bimodal speech recognition is illustrated. The error bars represent standard error of the mean. Asterisks indicate bimodal conditions with significantly different performance from the HAWB alone condition ($p < .05$, after Bonferroni correction).

Table 1.

Demographic information for participants based on relative performance with the CI alone and the HAWB alone (AzBio sentences at +10 dB SNR).

CI>HA (n=23)				HA>CI (n=10)			
Age (yrs) Mean (SEM)	Gender	Etiology (n)	Age (yrs) Mean (SEM)	Gender	Etiology (n)	Age (yrs) Mean (SEM)	Etiology (n)
65.5 (3.0)	10 Male 13 Female	Unknown (10) Noise (4) Genetic (3) Meningitis (1) Otosclerosis (2) Autoimmune (1) Menieres (1) Sudden SNHL (1)	68.1 (1.9)	4 Male 6 Female	Unknown (2) Noise (3) Skull Fracture (1) Menieres (2) Sudden SNHL (2)		
CI>HA (n=23)				HA>CI (n=10)			
CI Processor	N	Strategy	CI Processor	N	Strategy	CI Processor	Strategy
Cochlear			Cochlear				
N6	5	ACE	N6	5	ACE		
N5	7	ACE	Freedom	1	ACE		
Freedom	6	ACE					
AB			AB				
Naida Q70	1	Optima-P	Naida Q70	3	Optima P (1) Optima S (2) Optima S (1)		
Harmony	2	Hi Res-P, Fid120	Harmony	1			
Med-El							
Sonnet	1	FS 4P					
Combi 40+	1	FSP					

SEM = standard error of the mean

SNHL = sensorineural hearing loss

Comparison of age, device experience and audiometric characteristics of the non-implanted ear of participants as a function of group (CI>HA and HA>CI)

Table 2.

	CI>HA (N=23)	HA>CI (N=10)	t-test	P
	Mean	Mean	df=31	
Age	65.5	68.1	t=0.58	>.05 (two tailed)
CI experience (years)	3.1	2.7	t=0.45	>.05 (two tailed)
HA experience (years)	22.2	13.6	t=1.91	>.05 (two tailed)
LFPTA-dB HL (.25kHz, .5 kHz)	61.7	46.3	t=2.40	<.05 (two tailed)
MFPTA-dB HL (1kHz, 2kHz)	83.8	57.3	t=4.8	<.0001 (two tailed)
PTA-dB HL (.05kHz, 1kHz, 2kHz)	77.6	53.7	t=4.9	<.0001 (two tailed)
SLOPE (dB)	22.0	11.0	t=0.56	>.05 (two tailed)

LFPTA = low-frequency pure tone average (average of thresholds at 250 Hz and 500 Hz)

MFPTA= mid-frequency pure tone average (average of thresholds at 1000 and 2000 Hz)

PTA = pure tone average (average of thresholds at 500, 1000 and 2000 Hz)

SLOPE= (MFPTA-LFPTA)

Table 3.

Match to NAL-RP target as a function of highest frequency matched (up to 4 kHz) for each of the two groups (CI>HA, HA>CI). Columns show the number of participants with gain matched within 5 dB of target or matched within 10 dB of target.

Highest Frequency matched	CI>HA		HA>CI	
	Match +/-5 dB	Match +/-10 dB	Match +/-5 dB	Match +/- 10 dB
.5kHz	4			
1kHz	2			
2kHz	8	5		
3kHz	6	5	4	
4kHz	3	13	6	10
Total "n"	23	23	10	10

Table 4.

Speech recognition scores as a function of test condition (CI>HA group)

CI #	LFPTA (dB HL)	AZBio Sentence Test (+10 dB SNR)						CNC-30 Test Material					
		HAWB	CI	BM500	BM1k	BM2k	BMWB	HAWB	CI	BM500	BM1k	BM2k	BMWB
CI 195	35	36%	78%	92%	86%	92%	92%	24%	63%	69%	71%	59%	71%
CI 156	40	26%	68%	69%	75%	69%	70%	12%	43%	37%	45%	55%	47%
CI 223	43	2%	81%	70%	77%	75%	86%	20%	64%	66%	76%	68%	64%
CI 76	43	0%	57%	65%	64%	77%	66%						
CI 131	43	29%	75%	90%	98%	93%	CNT	8%	65%	80%	76%	78%	CNT
CI 34	48	DNT	67%	74%	71%	79%	74%						
CI 196	50	60%	66%	80%	77%	70%	91%	36%	62%	61%	53%	68%	53%
CI 70	50	DNT	83%	91%	90%	82%	87%						
CI 198	55	12%	18%	55%	52%	65%	CNT	0%	24%	18%	35%	26%	CNT
CI 97	60	42%	52%	60%	56%	72%	83%	44%	62%	78%	64%	80%	66%
CI 68	60	4%	58%	72%	75%	78%	79%						
CI 209	63							13%	20%	19%	21%	37%	31%
CI 63	65	0%	70%	86%	77%	83%	81%	4%	57%	58%	69%	58%	63%
CI 95	70	DNT	71%	65%	68%	67%	79%						
CI 157	70	0%	70%	70%	69%	68%	72%						
CI 92	70	DNT	84%	73%	86%	82%	86%						
CI 94	70	0%	76%	85%	79%	84%	90%						
CI 189	73	69%	81%	64%	72%	82%	91%	19%	56%	59%	67%	62%	57%
CI 89	73	30%	74%	77%	87%	89%	87%						
CI 202	75							25%	29%	25%	35%	30%	45%
CI 213	75	10%	65%	69%	70%	60%	69%	8%	73%	59%	77%	70%	65%
CI 161	78	48%	70%	76%	63%	76%	78%	13%	77%	74%	79%	67%	76%
CI 41	78	58%	81%	90%	88%	86%	84%	23%	61%	59%	56%	63%	55%
CI 91	83	20%	62%	88%	75%	92%	73%						
CI 160	93	DNT	58%	53%	45%	44%	57%	DNT	54%	70%	68%	60%	76%

LFPTA (dB HL) = low-frequency pure tone average in dB HL (frequencies are 250, 500 Hz)

CNT= could not test (because bandwidth did not differ from 2kHz bandwidth)

DNT = did not test

Bold font indicates bimodal scores significantly higher than CI score

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Table 5.

Speech recognition scores as a function of test condition (HA>CI group)

CI #	LFPTA (dB HL)	AZBio Sentence Test (+10 dB SNR)						CNC-30 Test Material					
		CI	HAWB	BM500	BM1k	BM2k	BMWB	CI	HAWB	BM500	BM1k	BM2k	BMWB
CI 8	18	26%	82%	89%	68%	77%	79%	51%	75%	85%	87%	85%	86%
CI 180	18	55%	84%	82%	82%	70%	83%	24%	31%	56%	54%	56%	55%
CI 192	35	74%	82%	89%	86%	80%	83%	57%	65%	65%	69%	81%	80%
CI 187	40	34%	91%	56%	67%	79%	90%	46%	49%	45%	55%	60%	70%
CI 201	43	9%	80%	47%	72%	84%	91%	17%	29%	25%	43%	57%	60%
CI 179	53	4%	56%	7%	16%	21%	47%	12%	26%	12%	17%	15%	19%
CI 206	58	10%	62%	27%	19%	45%	60%	10%	23%	17%	26%	30%	34%
CI 203	63	14%	67%	13%	31%	27%	70%	16%	23%	11%	19%	21%	27%
CI 209	63	26%	53%	22%	14%	44%	69%						
CI 202	75	48%	71%	47%	50%	73%	86%						

LFPTA = low-frequency pure tone average in dB HL (frequencies are 250 and 500 Hz)

Red font indicates bimodal scores significantly poorer than HAWB score.**Bold font** indicates bimodal scores significantly higher than HAWB score