Research Article

Effects of Removing Low-Frequency Electric Information on Speech Perception With Bimodal Hearing

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Purpose: The objective was to determine whether speech perception could be improved for bimodal listeners (those using a cochlear implant [CI] in one ear and hearing aid in the contralateral ear) by removing low-frequency information provided by the CI, thereby reducing acoustic–electric overlap.

Method: Subjects were adult CI subjects with at least 1 year of CI experience. Nine subjects were evaluated in the CI-only condition (control condition), and 26 subjects were evaluated in the bimodal condition. CIs were programmed with 4 experimental programs in which the low cutoff frequency (LCF) was progressively raised. Speech perception was evaluated using Consonant-Nucleus-Consonant words in

quiet, AzBio sentences in background babble, and spondee words in background babble.

Results: The CI-only group showed decreased speech perception in both quiet and noise as the LCF was raised. Bimodal subjects with better hearing in the hearing aid ear (< 60 dB HL at 250 and 500 Hz) performed best for words in quiet as the LCF was raised. In contrast, bimodal subjects with worse hearing (> 60 dB HL at 250 and 500 Hz) performed similarly to the CI-only group.

Conclusions: These findings suggest that reducing low-frequency overlap of the CI and contralateral hearing aid may improve performance in quiet for some bimodal listeners with better hearing.

Cochlear implantation criteria currently include individuals who have aidable hearing—that is, bilateral severe-to-profound sensorineural hearing loss (HL) across the speech frequencies 250–8000 Hz (Carlson et al., 2015; Gifford, Dorman, Shallop, & Sydlowski, 2010; Heman-Ackah, Roland, Haynes, & Waltzman, 2012; Sampaio, Araújo, & Oliveira, 2011). Cochlear implantation has led to significant improvements over preimplantation amplification for many individuals, including providing improved open set recognition (Carlson et al., 2015; Firszt, Holden, Reeder, Cowdrey, & King, 2012; Gifford et al., 2010). With these improved outcomes, cochlear implant (CI) candidacy guidelines for various companies have recently expanded to include individuals with HL in the moderate as well as the severe-to-profound HL range. In addition, advances in electrode design, technology, and surgical techniques have

enabled preservation of hearing thresholds in the implanted ear (Gstoettner et al., 2004, 2006; Machado de Carvalho et al., 2013; Mowry, Woodson, & Gantz, 2012; Turner, Gantz, & Reiss, 2008a; Usami et al., 2014).

The increased implantation of individuals with aidable hearing and the preservation of hearing in the implanted ear allow the use of two listening modalities: *bimodal hearing*, in which a CI is used with a hearing aid (HA) worn in the contralateral, nonimplanted ear (e.g., Dooley et al., 1993), and *hybrid* or *electro-acoustic stimulation* (EAS), in which individuals with residual hearing in the implanted ear use the CI together with an HA in the same ear (Gantz & Turner, 2003; Gstoettner et al., 2004). Hybrid and EAS are names derived by the manufacturer, Cochlear and MED-EL, respectively. Individuals using these multiple hearing modalities compared with use of a CI alone may demonstrate measurable improvements in speech perception both in quiet and in noise (Ching, Incerti, & Hill, 2004; Ching, van Wanrooy, & Dillon, 2007; Dettman et al., 2004; Firszt, Reeder, & Skinner, 2008; Flynn & Schmidtke, 2004; Gantz & Turner, 2003; Gstoettner et al., 2004; Most, Gaon-Sivan, Shpak, & Luntz, 2012; Mowry et al., 2012; Potts, Skinner, Litovsky, Strube, & Kuk, 2009; Straatman, Rietveld, Beijen, Mylanus, &

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Mens, 2010; Tuner et al., 2008a; Turner, Reiss, & Gantz, 2008b), sound localization (Ching et al., 2004, 2007; Firszt, et al., 2008; Flynn & Schmidtke, 2004; Potts et al., 2009), music perception (Bartov & Most, 2014; Flynn & Schmidtke, 2004; Mowry et al., 2012; Turner et al., 2008b), and voice recognition (Flynn & Schmidtke, 2004), as well as subjective benefits of access to binaural hearing and sound quality from combined acoustic and electric hearing (Ching et al., 2004; Firszt et al., 2008; Flynn & Schmidtke, 2004; Potts et al., 2009). However, the benefit of the addition of amplification to CI use is variable across individuals, particularly for speech perception, and an effective clinical protocol for programming of multiple hearing modalities has not yet been determined, as not every parameter has been investigated (Blamey & Saunders, 2008; Dorman, Spahr, Loizou, Dana, & Schmidt, 2005; Heo, Lee, & Lee, 2013; Incerti, Ching, & Cowan, 2013; Ullauri, Crofts, & Wilson, 2007; Usami et al., 2014; Yamaguchi & Goffi-Gomez 2013; Zhang, Dorman, Gifford, & Moore, 2014).

A few recent studies have assessed fitting parameters for bimodal listeners by adjusting the frequency range of either the HA or the CI. For example, one study manipulated the HA frequency range in the nonimplanted ear, and concluded that optimal bimodal benefit for speech perception in quiet and noise is obtained when HA amplification includes all frequencies that are considered acoustically aidable; acoustic aidability was defined as thresholds at or below 95 dB HL for 250–2000 Hz, and at or below 115 dB HL for 4000 Hz (Neuman & Svirskey, 2014). Another study showed that amplification in the mid- to high-frequency regions should be removed from dead regions for improved speech perception, music quality, and speech quality; dead regions are defined as frequency regions in which responses to sound are due to excitation of adjacent frequencies with lower thresholds than the test frequency (Zhang et al., 2014). Just one study manipulated the CI, by raising the lowest frequency encoded by the CI to complement rather than overlap with the aidable acoustic frequency range, and found no effect on bimodal performance; however, that study only evaluated speech reception thresholds (SRTs) for sentences presented in noise, and did not look at effects on speech perception in quiet (Green, Faulkner, & Rosen, 2014). In addition, the number of subjects was small, with only eight subjects studied, and only two of those subjects had hearing thresholds better than 70 dB HL (Green, Faulkner, & Rosen, 2012; Green et al., 2014).

In contrast, studies in patients with Hybrid or EAS devices have clearly shown that raising the lowest frequency encoded by the CI (i.e., from 188 Hz to 500 Hz), and thus reducing overlap between electric and acoustic frequencies, improved speech perception benefits in noise, but not quiet (Karsten et al., 2013; Vermeire, Anderson, Flynn, & Van de Heyning, 2008). For example, in the Hybrid study by Karsten et al. (2013), SRTs in background babble significantly improved for individuals using the Hybrid CI when programmed in the *meet* condition, in which the low-frequency residual hearing was acoustically amplified and frequencies above the residual hearing region were stimulated

electrically, in comparison to the *overlap* condition, in which there was a mid-frequency region being stimulated both electrically and acoustically. This finding contrasts with the Green et al. (2014) study, which showed no benefit of reducing frequency overlap between acoustic and electric hearing. The reason for the discrepancy is not clear, but one potential reason is that the degree of HL was greater in the acoustic ears of the bimodal patients in the Green study, compared with the Hybrid patients in the Karsten et al. (2013) study. In particular, bimodal patients with less usable residual hearing may not show effects of reducing overlap. The Green et al. (2014) study showed only the effects of overlap on group averaged results without determining whether there were effects on the basis of the amount of residual hearing.

The purpose of this study was to determine whether raising the low cutoff frequency (LCF) of the CI, and thus reducing the low-frequency overlap between the acoustic and electric hearing, increases benefit in bimodal listeners similarly to improvement seen in Hybrid users. Performance in this study was extended from the Green et al. (2014) study, which is the only study published in which the CI was manipulated rather than simply the HA, to evaluate word and sentence recognition percent correct scores, as well as SRTs in noise, in a larger group of bimodal subjects, including a larger range of HL. In addition, the results were parsed by amount of low-frequency residual hearing in the nonimplanted ear to determine whether the amount of residual hearing is a factor in bimodal benefit with decreased acoustic and electric overlap. A control group was also tested in the CI-only condition to rule out that any condition effects were not simply due to decreasing the low-frequency information through the CI, independent of the acoustic–electric overlap.

For the bimodal condition, it was hypothesized that raising the LCF and reducing acoustic–electric overlap would improve speech recognition performance, especially for individuals with more usable residual hearing in the contralateral ear. For the CI-only condition, it was hypothesized that raising the LCF would lead to worsened performance, because of the reduction in low-frequency electric information without access to equivalent information from low-frequency acoustic hearing.

Materials and Method

Study Design

The LCF was systematically varied in order to investigate effects of incremental changes in electric cutoff frequencies, in both a bimodal and control CI-only condition. The CI-only condition consisted of an unilateral CI without an HA or access to acoustic information, and was used as a control condition to determine whether effects of raising the LCF were due to the reduced low-frequency information provided to the CI, or to reduced overlap of the CI with the low-frequency acoustic hearing. Effects were also examined as a function of the amount of low-frequency

residual hearing in the nonimplanted ear for the bimodal condition.

Subjects

The Institutional Review Board at Oregon Health & Science University approved this research study. Research subjects were recruited from the Oregon Health & Science University CI Program in the Department of Otolaryngology, Head & Neck Surgery. Research subjects were compensated for their participation time in the study.

Twenty-six adults (age range = 44–87 years, mean age = 71 years, *SD* age = 17 years; men = 15, women = 11) were tested in the bimodal condition, and nine adult CI users (age range = 28–77 years, mean age = 59 years, *SD* age = 11 years; men = 5, women = 4) were tested in the CI-only condition. Three of the study subjects (CI/CIHA25, CI/CIHA49, CI/CIHA54) were enrolled in both the bimodal and CI-only groups. All subjects had greater than 12 months of CI experience and were native English speakers. In the bimodal group, subjects had either the MED-EL ($n = 3$; all electrodes active) or Cochlear ($n = 23$; no more than three basal electrodes deactivated) CI devices, and in the CI-only group, subjects had the Cochlear CI device ($n = 9$; all electrodes active).

Test Conditions and Device Fitting

CI Programming and Experimental Conditions (All Subjects)

A laboratory Freedom processor was used for subjects with a Cochlear internal device, and a laboratory Opus II processor was used for subjects with a MED-EL internal device. All CI processors were programmed with four experimental programs with progressively raised LCFs as shown in Table 1. For Cochlear subjects, Condition 1 maintained the full CI frequency range. For MED-EL subjects, Electrode 1 was disabled in Condition 1 in order to provide a similar baseline LCF and overall frequency range as the Cochlear subjects. The LCF for Conditions 2–4 was gradually raised from the default full CI frequency range for each manufacturer.

The default manufacturer frequency-to-electrode allocations were maintained for all conditions to minimize the need to adapt to spectral shifts. The LCFs were raised by deactivating electrodes via setting current levels to zero on low-frequency designated electrodes instead of using the software deactivation option; this procedure maintained the number of active electrodes and thus the default frequency

allocations for each electrode. An exception was made for one Cochlear subject (CIHA28) who had an atypical LCF of 100 Hz for everyday use, which was not maintained in the experimental programs; instead, the default manufacturer frequency allocations were manipulated for testing to be consistent with the remainder of the subjects.

Current levels, pulse widths, and pulse rate were based on the patient's own CI program settings. The subjective volume of the CI was adjusted by changing the overall electric stimulation level control on the processor to be comfortable and loudness-balanced with the HA for Condition 1, in which all or nearly all electrodes were active. The same volume determined for Condition 1 was used for all four experimental programs. CI features including automatic sensitivity control and automatic dynamic range optimization, and directional microphones were deactivated.

Hearing Aid Programming (Bimodal Subjects Only)

For subjects with residual hearing who were tested in the bimodal condition, pure tone unaided hearing thresholds in the nonimplanted ear were evaluated using conventional audiometry procedures with a Grason-Stadler 61 audiometer and Etymotic Research 3A insert earphones (for individual and group mean audiograms, see online supplemental materials, Supplemental Table 1). Real ear aided verification measurements were obtained in the Audioscan Verifit test box to determine whether HAs met target output levels for average speech inputs (long-term average speech spectrum level of 65 dB SPL). Target output levels were defined using the National Acoustic Laboratories' nonlinear fitting procedure, version 1 (NAL-NL1) gain prescription formula, on the basis of subjects' hearing thresholds in the nonimplant ear and measured real-ear-to-coupler differences (Bryne et al. 2001). NAL-NL1 targets were considered to be met when real ear aided measures were no more than 10 dB below targets.

Subjects' own HAs were used when possible to minimize the need to adapt to new HAs, with the exception of those with HAs that did not meet NAL-NL1 targets or that had additional features (i.e., frequency transposition) activated. Eight bimodal subjects wore HAs that satisfied these criteria and used their own HAs during testing. The remaining 18 bimodal subjects wore HAs that did not satisfy these criteria, so either a laboratory-owned Phonak Naida S IX UP ($n = 16$), or Oticon Chili SP 9 ($n = 1$), or Oticon 380P ($n = 1$) HA was programmed to meet NAL-NL1 targets. HA features including noise reduction, directional microphone, and frequency transposition were deactivated.

Table 1. Cochlear implant manipulated low cutoff frequencies for each condition.

Condition	Frequency range (Cochlear)	Frequency range (MED-EL)
1	188–7938 Hz (all electrodes active)	170–8500 Hz (electrode 1 deactivated)
2	438–7938 Hz (electrodes 22–21 deactivated)	469–8500 Hz (electrodes 1–3 deactivated)
3	688–7938 Hz (electrodes 22–19 deactivated)	690–8500 Hz (electrodes 1–4 deactivated)
4	938–7938 Hz (electrodes 22–17 deactivated)	982–8500 Hz (electrodes 1–5 deactivated)

Most real ear aided measures were no more than 5 dB below NAL-NL1 targets. However, it was not possible to meet targets for one subject at 1000 Hz (CI19), two subjects at 2000 Hz (CI34 and CI53), and five subjects at 6000 Hz (CI24, CI49, CI72, CI73, and CI76).

Speech Perception Testing

All subjects were tested acutely in one to two sessions without time to adjust to the new CI settings (or HA settings if changed). The testing was conducted in a double-walled sound-treated booth with recorded speech stimuli presented at a level of 60 dBA at zero degrees azimuth from a loudspeaker at a distance of 1 m from the subject. The experimental conditions were randomized in order to control for any learning effects or fatigue during speech perception testing. Testing was completed in 1 day for all subjects without time to adapt to the experimental conditions, with the exception of time to adapt during the practice rounds for each test and condition.

Subjects were tested on the following speech perception tests: (a) Consonant-Nucleus-Consonant (CNC) word test in quiet (Peterson & Lehiste, 1962); (b) AzBio sentences in 10-talker babble with signal-to-noise ratio (SNR; +5–20 dB) selected to avoid ceiling or floor effects (Spahr & Dorman, 2005, 2007; Spahr et al., 2012); (c) spondee words (two-syllable words with equal stress) in four-talker background babble (Turner, Gantz, Vidal, Behrens, & Henry, 2004). Most subjects completed all three tasks; however, four subjects completed only a subset of tasks. Subjects CIHA19 and CIHA69 did not return to complete all the AzBio tests. Subject CIHA21 did not return to complete the CNC test. CIHA28 was diagnosed with cancer before the second visit, and as a result of chemotherapy experienced a significant decrease in hearing before he could be tested on the AzBio and CNC tests.

For the CNC and AzBio speech perception tests, subjects responded to test stimuli by repeating the word(s) they heard, which were scored by an audiologist. The CNC and AzBio test scores were calculated by obtaining percent correct word score for each list tested. For the spondee words in babble test, subjects chose which of 12 spondee words was heard from a display on a computer touch screen. The SNR was adaptively varied to find the SNR at which the subject was able to score 50% correct spondee score. A 1-up, 1-down adaptive procedure was used starting at a +10 dB SNR and varying the SNR in 2-dB steps depending on whether the subject selected the correct word or not. The procedure was terminated at 14 reversals, and the 50% SNR was computed as the average of the last 10 reversals. A positive SNR value indicated the speech signal level needed to be louder than the noise for 50% correct recognition, whereas a negative SNR value indicated the speech could be softer in level compared with the noise for 50% correct recognition. Two CNC word lists, two AzBio sentence lists, and four spondee test repeats were completed per experimental condition by each subject. The average score for each experimental condition was calculated for use in the analysis.

Analysis

A mixed model, which generalizes repeated measures analysis of variance, was used to determine the effects of LCF condition for the control group and the CI-only group, and to determine the effects of LCF condition, hearing thresholds in the nonimplanted ear, and measured real ear values for the bimodal group along with interactions of these factors. For the CI-only group, condition was set as a factor with random subject intercepts. For the bimodal group, condition was set as a factor, and low-frequency hearing threshold (average of 250 and 500 Hz) in the nonimplanted ear was included as a covariate along with random subject intercepts. The AzBio sentence analysis for the bimodal group benefited from a logit transformation of the outcome variable percent correct. The fit of the models was evaluated with studentized residuals. The model results were plotted using a model-based mean score by condition with standard error bars for the CI-only group and with the addition of hearing threshold categories implemented in the model for the bimodal group.

Results

The CI-only group showed clear decreases in speech recognition performance as the LCF of the CI was raised for all tests. Figure 1, panels A and B, shows the CI-only group decrease in score for the CNC words in quiet and AzBio sentences in noise tests, respectively. Figure 1, panel C, shows that higher (easier) SNRs were also needed on the spondee test as the LCF was raised from Condition 1 to Condition 3. All individuals in the CI-only group showed the same trends as the group average, in which speech perception scores in quiet and noise worsened as the LCF was raised and less low-frequency information was transmitted.

When data from all subjects were averaged together in the bimodal group, very little change was seen as the LCF of the CI was raised (not shown). Individual examples in Figure 2, however, show differences across subjects, depending on the amount of residual hearing. Figure 2, panels A–D, shows data for subject CIHA32 with better low-frequency hearing in the nonimplanted ear, in the moderately severe sloping to profound range. This subject improved performance from 50% to nearly 70% correct on the CNC words in quiet as the LCF was raised from Condition 1 through Condition 3. Figure 2, panels E–H, shows a bimodal subject CIHA71 with poorer low-frequency hearing in the nonimplanted ear in the severe sloping to profound range relative to subject CIHA32. This subject showed a similar improvement from 45% to 65% correct on CNC words with incremental removal of low frequencies from the CI from Condition 1 to Condition 3, followed by a decline in performance from Conditions 3 to 4. Both bimodal subjects CIHA32 and CIHA71 showed negligible differences across conditions for the AzBio and spondee tests. Figure 2, panels I–L, shows another bimodal subject CIHA75 with hearing thresholds in the nonimplanted ear in the

Figure 1. Group average test scores for the cochlear implant-only group as a function of low cutoff frequency (LCF) condition. LCF conditions from 1 to 4 represent frequency-to-electrode allocations in which the lower frequency edge of the allocation is increasing, while the upper frequency edge of the allocation is held constant. Error bars indicate the standard error. (A) Percent correct scores for Consonant-Nucleus-Consonant (CNC) words in quiet. (B) Percent correct scores for AzBio sentences in the presence of background talkers. (C) Signal-to-noise ratios for 50% correct recognition of spondee words in background talkers.

profound range, the poorest hearing thresholds of the three bimodal examples. This subject demonstrated declines in scores from 65% to 35% and 83% to 50% for the CNC and AzBio tests, respectively, as LCF was raised from Conditions 1 to 3, and was most similar to the CI-only subjects.

When subjects were divided into two groups on the basis of average hearing thresholds at 250 and 500 Hz—that is, a *better hearing* group with average thresholds less than 60 dB HL ($n = 10$) and a *poorer hearing* group with average thresholds greater than 60 dB HL ($n = 16$)—clear group trends were seen, as shown in Figure 3, panels A–C. First, better performance for all tests regardless of LCF condition was observed for the better hearing group compared with the poorer hearing group. In addition, trends with LCF condition differed for the two groups. For instance, the better hearing group showed improvements in CNC word score with increasing LCF condition from 1 to 4, whereas the poorer hearing group showed the opposite trend of decreases in scores with increasing LCF condition (Figure 3, panel A). Scores on AzBio sentences in babble were more complex for the better hearing group, improving slightly from Conditions 1 to 2 and then decreasing slightly from Conditions 2 to 4, whereas the poorer hearing group showed straight declines in scores from Conditions 1 to 4 (Figure 3, panel B). The SNRs required for 50% performance on spondees in babble were relatively similar across conditions for the better hearing group, whereas the poorer hearing group required easier (more positive) SNRs with increasing LCF condition (Figure 3, panel C).

Figure 4 shows the distributions of best LCF condition—that is, condition with the best score, which was defined as at least a 10% improvement in word or sentence score over the worst condition—or the best SNR, which was defined as 1 dB more negative or less positive SNR than other conditions. In the CI-only group, most subjects performed best with Condition 1, with the lowest LCF and widest frequency range for CNC words in quiet and AzBio

sentences in babble. No optimal condition was seen for the spondee test. In the bimodal group, unlike the CI group, optimal condition was not uniform. Instead, some bimodal subjects performed best in Condition 1, others in Condition 2, and so on. In addition, optimal condition often varied with the specific speech perception test. Condition 1 was often the best condition for AzBio sentences in noise, and Condition 2 was often the best condition for the spondee test. For CNC words in quiet, the best condition was distributed uniformly across conditions. When analyzed for correlations of best condition (1–4) with the audiometric cutoff frequency at which thresholds became worse than 60 dB HL, a highly significant positive correlation was seen ($R = .65$, $p = .007$; Pearson two-tailed correlation test). This correlation remained significant for a range of audiometric threshold criteria between 40 dB and 70 dB ($p < .05$). In other words, bimodal listeners with higher audiometric cutoff frequencies (a wider range of aidable low-frequency hearing) were more likely to do best with CNC words in higher LCF conditions.

Mixed models were used to evaluate the significance of trends for each group. For the CI-only group, the mixed model demonstrated significant effects for LCF condition for all three speech perception tests (all tests $p < .0001$). As suggested by the summary data plotted in Figure 1, the condition effect is a straightforward decline in scores with increasing LCF. Figure 5 shows model predictions of the CI-only data, which predicts a decrease in performance as the LCF is raised.

For the bimodal group, the mixed model also demonstrated significant effects of LCF condition for the CNC and AzBio tests, but not for the spondee test (CNCs $p < .0001$; AzBio $p = .0065$; spondees $p = .5312$). A significant effect of HL was also observed for all three tests with the exception of the spondee test (CNCs $p = .0401$; AzBio $p = .0129$; spondees $p = .2258$), as well as a significant interaction between the two factors of condition and HL for CNCs and AzBio tests, but not for the spondee test (CNCs $p < .0001$;

Figure 2. Example bimodal cochlear implant subjects' contralateral, nonimplanted ear hearing thresholds on audiogram and test scores graphed as a function of low cutoff frequency (LCF) condition. Plotted as in Figure 1 with the top graphs (panels A–D) displaying results for a bimodal subject with average hearing threshold < 60 dB HL at 250 and 500 Hz; middle graphs (panels E–H) showing results for a bimodal subject with average hearing threshold at 250 and 500 Hz > 60 dB HL and < 80 dB HL; bottom graphs (panels I–L) displaying results for a bimodal subject with average hearing threshold > 80 dB HL at 250 and 500 Hz. CNC = Consonant-Nucleus-Consonant.

AzBio $p < .0001$; spondees $p = .2715$). In other words, significant effects were seen, but the direction of the trends depended on the amount of residual hearing as described below.

For the bimodal group, the effects of LCF condition, HL, and their interaction were examined further by estimating the mean speech perception score at three different hearing levels. Mean speech perception scores were computed from the mixed model for thresholds fixed at 40, 60, and 80 dB HL. Figure 6 shows the model predictions of the bimodal data. For an individual with average thresholds of 40 dB HL at 250 and 500 Hz, the model predicts an increase in score as the LCF is raised for CNC words (solid line with squares, Figure 6, panel A). In contrast, for an individual with average thresholds of 60 dB HL or 80 dB HL at 250 and 500 Hz, the model predicts a decrease in score when LCF is raised (dashed line with stars and dotted line

with diamonds, Figure 6, panel A). These predictions for CNC word scores are consistent with the trends for the individual examples with varying degrees of HL, as shown in Figure 2, as well as with the group CNC word data parsed by HL as shown in Figure 3, panel A. For the AzBio test, the model similarly shows different predictions on the basis of degree of HL. Predicted changes in score for individuals with thresholds of 40 dB HL are nonmonotonic, with a slight increase from Conditions 1 to 2 as the LCF is raised, followed by a drop in score from Conditions 2 to 4 (solid line with squares, Figure 6, panel B). For individuals with average thresholds of 60 and 80 dB HL, again the AzBio scores are predicted to decrease as the LCF is raised (dashed line with stars and dotted line with diamonds, Figure 6, panel B). These predictions are again consistent with the group AzBio score data parsed by HL in Figure 3, panel B. For the spondee test, the predictions form parallel trends,

Figure 3. Group average test scores for the bimodal cochlear implant (CI) group divided into two groups on the basis of average hearing thresholds at 250 and 500 Hz (≤ 60 dB HL and > 60 dB HL) as a function of low cutoff frequency (LCF) condition. Plotted as in Figure 1.

consistent with the lack of interactions observed between HL and condition (Figure 6, panel C). Bimodal subjects did not show significant effects of measured real ear relative to target values across conditions (not shown), as expected given that real ear measurements demonstrated that nearly all NAL-NL1 targets were met.

Discussion

The results demonstrate that reducing the low-frequency information provided to the CI is detrimental, as expected, for understanding speech in quiet and noise for individuals who use a CI alone and for individuals who use a CI and contralateral HA but have poorer, or less aidable, low-frequency hearing in the nonimplanted ear (> 60 dB HL). However, individuals who use a CI and HA in the nonimplanted ear and who have better, or more aidable, low-frequency hearing in the nonimplanted ear

(< 60 dB HL), may demonstrate a benefit in understanding speech in quiet when some low-frequency information encoded in the CI is removed. One possible interpretation is that the removal of low-frequency information from the CI for these individuals, which reduces overlap with low-frequency acoustic amplification provided to the non-implanted ear, prevents interference with the contralateral HA in these individuals with better residual hearing.

This phenomenon may be related to previous findings of abnormally broad binaural fusion of spectral information across ears in bimodal listeners (Reiss, Ito, Eggleston, & Wozny, 2014). Abnormally broad fusion has been shown to lead to averaging and thus potential smearing of spectral information processed by the CI and HA, especially when there is a pitch mismatch between ears (Reiss et al., 2014). Averaging of spectrally mismatched information may lead to distortion of important spectral information needed for understanding speech, such as vowel formant frequency, or consonant voicing or place information.

Figure 4. Distribution of best low cutoff frequency (LCF) condition, the condition that gave the highest score, for each test. Different bar shades indicate the best conditions for different tests. (A) Cochlear implant (CI)-only group distribution. (B) Bimodal CI group distribution. CNC = Consonant-Nucleus-Consonant.

Figure 5. Cochlear implant (CI)-only group model with predicted test scores as a function of low cutoff frequency (LCF) condition. Plotted as in Figure 1. CNC = Consonant-Nucleus-Consonant; SNR = signal-to-noise ratio.

The findings for the spondee in background babble test are similar to the Green et al. (2014) study but differ from the Karsten et al. (2013) study, which found significant effects of condition on SRTs in background babble. One explanation for the discrepancy may be the differences in the number of talkers comprising the background babble; the background consisted of four talkers in this study and 20 talkers in the Green study, which may be more noise-like than babble-like compared with the two talkers in the Karsten et al. (2013) study. The balance between energetic and informational masking changes with the number of talkers, with clear differences between one and two talkers, and two and four talkers (Rosen, Souza, Ekelund, & Majeed, 2013). The effects observed in the Karsten et al. (2013) study may have been due to reductions in informational masking with less overlap, whereas informational masking may not have been present or more variable in the current study and the Green study.

The benefits for bimodal listeners with better hearing in the nonimplanted ear are similar to those seen in Hybrid or EAS users in that speech perception improves with less overlap of the CI and HA in the same ear (Karsten et al.,

2013; Vermeire et al., 2008). This study showed that the improvement in speech perception for the bimodal subjects in this study was in quiet, unlike the Hybrid study that found the benefit only in noise (Karsten et al., 2013). One possible explanation for the difference is that different speech materials were used in this study; the CNC word test, which measures both vowel and consonant perception, was used instead of the consonant-only test used in the Karsten et al. (2013) study. It may be that formant frequencies required for vowel identification are affected more by acoustic-electric overlap than cues for consonant identification, which are less dependent on spectral information.

In addition, the subjects in this study were not provided with time to adapt to the CI experimental program parameters, which was provided to the Hybrid CI subjects in the Karsten et al. (2013) study; the majority of the subjects in this study were also tested with laboratory HAs without the benefit of experience. One study evaluating Hybrid CI users by Reiss, Perreau, and Turner (2012) found the benefit of manipulating CI overlap with acoustic hearing in the nonimplanted ear for individuals who lost hearing in the implanted ear can change over time. However, this study

Figure 6. Bimodal cochlear implant (CI) group model depicting predicted test scores as a function of low cutoff frequency (LCF) condition, and subjects subdivided on the basis of the degree of residual hearing, as indicated by different line shades and symbols. (A) Consonant-Nucleus-Consonant (CNC) word scores. (B) AzBio sentence in noise scores. (C) Spondee in babble signal-to-noise ratios (SNRs). For each plot, the solid line with squares, dashed line with stars, and dotted line with diamonds show predicted results for the group with average low-frequency thresholds of 40, 60, and 80 dB HL, respectively. As shown, the group with 40 dB HL thresholds differed from the others in the improvement of CNC word scores as LCF was raised and low-frequency overlap between the hearing aid and CI was reduced.

evaluated only three subjects, which limit the generality of the results. Further investigation is warranted to assess whether subjects are able to adapt to the experimentally manipulated CI and HA settings.

Another possible explanation is that different mechanisms of interference may be occurring for the two modes of stimulation. In the Hybrid case, within-ear interference may be due to concurrent acoustic and electric stimulation of the same hair cells or spiral ganglion neurons in the auditory periphery. In the bimodal case, the interference is occurring across ears and therefore more likely to be exclusively central in origin; this interference may be related to the abnormally broad fusion observed in bimodal listeners (Reiss et al., 2014).

Further studies on bimodal fittings are warranted to determine the impact of increasing the LCF for individuals who have more usable low-frequency hearing in the non-implanted ear and who wear an HA on performance on sound localization, spatially separated speech in noise tasks, music perception, and subjective assessment in real-world environments. Furthermore, this study included adult subjects only and should be expanded to include children to determine whether the findings in this study are applicable to children who are bimodal listeners.

In addition, it may be informative to examine whether or not other HA prescription formulas result in differing amounts of interference of the CI and HA for bimodal listeners. The NAL-NL1 fitting strategy was implemented in this study and in the Karsten et al. (2013) Hybrid study, whereas the Vermeire et al. (2008) EAS study used Oticon's proprietary fitting rationale. Both of these fitting strategies apply the half-gain rule for amplification. However, newer prescriptions have been developed in recent years. For instance, the National Acoustic Laboratories Nonlinear 2 strategy takes into account additional variables for prescription of gain, including previous HA experience, gender preferences, and severe-to-profound HL (Keidser, Dillon, Carter, & O'Brien, 2012). The NAL-Revised, Profound fitting formula is another strategy developed specifically for individuals with severe-to-profound HL, which prescribes less low-frequency gain for flat and rising HL configurations and more high-frequency amplification for steeply sloping HL (Byrne, Dillon, Ching, Katsch, & Keidser, 2001). The Desired Sensation Level strategy is another HA fitting rationale that is considered to have a greater emphasis on audibility in that more amplification is prescribed in the high frequencies, particularly for children, given the importance of these sounds for their speech and learning needs (Pittman 2008; Scollie et al., 2005). It may be that the selection of the appropriate HA fitting formula should be determined separately for each individual on the basis of interactions between the CI and HA, as well as degree of HL, age, experience, and other factors.

Overall, the results of this study demonstrate that in the bimodal condition, speech recognition performance in quiet can be improved by decreasing the overlap between acoustic and electric hearing, particularly for individuals with better residual hearing in the nonimplanted ear. Further,

these results show that the outcomes of research studies in bimodal listeners need to be parsed on the basis of the amount of residual hearing; important trends may be missed if all bimodal subjects are grouped together independent of their variability in thresholds.

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