Published in final edited form as:

Ear Hear. 2013 September ; 34(5): 553–561. doi:10.1097/AUD.0b013e31828e86e8.

The effect of hearing aid bandwidth on speech recognition performance of listeners using a cochlear implant and contralateral hearing aid (bimodal hearing)

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Abstract

Objectives—The purpose of this study was to determine how the bandwidth of the hearing aid (HA) fitting affects bimodal speech recognition of listeners with a cochlear implant (CI) in one ear and severe-to-profound hearing loss in the unimplanted ear (but with residual hearing sufficient for wideband amplification using NAL-RP prescriptive guidelines; unaided thresholds no poorer than 95 dB HL through 2000 Hz).

Design—Recognition of sentence material in quiet and in noise was measured with the CI alone and with CI plus HA as the amplification provided by the hearing aid in the high and mid-frequency regions was systematically reduced from the wideband condition (NAL-RP prescription). Modified bandwidths included upper frequency cutoffs of 2,000, 1,000 or 500 Hz.

Results—On average, significant bimodal benefit was obtained when the hearing aid provided amplification at all frequencies with aidable residual hearing. Limiting the hearing aid bandwidth to only low frequency amplification (below 1000 Hz) did not yield significant improvements in performance over listening with the CI alone.

Conclusion—These data suggest the importance of providing amplification across as wide a frequency region as permitted by audiometric thresholds in the hearing aid used by bimodal users.

Keywords

cochlear implant; hearing aid; bimodal benefit; speech recognition

Introduction

In the past, cochlear implant (CI) users had very little residual hearing in the unimplanted ear. As a consequence, few used both an implant and a hearing aid (HA). Now, as a result of changing audiometric criteria for cochlear implantation, there is a growing population of persons with a unilateral CI who have measurable hearing in the contralateral ear. The amount of residual hearing in the unimplanted ear of bimodal candidates can vary

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Portions of this paper were presented as a poster at the 2011 Conference on Implantable Auditory Prostheses, Pacific Grove, CA.

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considerably. Thresholds in the low frequency region might range from near-normal hearing to severe or profound loss. Typically thresholds at 1000 Hz and higher frequencies are in the severe-to-profound range.

Many of these people might benefit from the use of a HA in addition to their CI. A HA can provide access to low-frequency acoustic cues (e.g., fundamental frequency, lower harmonics) and provide fine structure information not available through the CI. Numerous studies provide evidence that bimodal listening (use of a HA in conjunction with the CI) can improve speech recognition performance in quiet conditions and may be especially helpful when listening in noise (e.g., Hamzavi et al. 2004; Dunn et al. 2005; Kong et al. 2005; Ching et al. 2006; Mok et al. 2006; Gifford et al. 2007; Dorman et al. 2008; Potts et al. 2009). However, for some people there is no improvement in speech recognition when the HA is used in addition to the CI (e.g., Tyler et al. 2002; Ching et al. 2004b; Dunn et al. 2005; Morera et al. 2005, Mok et al. 2006). In a small number of cases, use of a HA in the ear contralateral to the implant may actually degrade speech recognition performance (e.g., Armstrong et al. 1997; Dunn et al. 2005; Litovsky et al. 2006, Mok et al. 2006).

The requirements for fitting the HA to be worn in conjunction with the CI are not well understood. In many studies reporting on bimodal (CI+HA) performance, the evaluation has been carried out using the listener's personal hearing aid. Unfortunately, information about the characteristics of the hearing aid and the adequacy of the hearing aid fitting are frequently not provided. In consequence, little is known about how the listener's residual hearing and the characteristics of the hearing aid might affect bimodal benefit or whether the approach to fitting the hearing aid might need to be modified when it is to be used in conjunction with a cochlear implant.

It may be the case that a hearing aid fitting that only amplifies low frequencies (1) may be sufficient to provide bimodal benefit (Zhang et al. 2010), (2) makes it possible to provide more hearing aid gain in the low-frequency region and (3) in some cases, may be a means of preventing interference between information provided by the HA and the CI (Mok et al. 2006). Typically, hearing aid prescriptive procedures have the goal of providing audibility over as wide a frequency range as possible. But prescriptive procedures differ in recommendations of insertion gain as a function of frequency and also differ with regard to the recommended hearing aid bandwidth (Johnson & Dillon, 2011). The ability to make sound audible through the hearing aid at high frequencies (at and above 3000 Hz) will be governed by the degree of hearing loss. Often it is not possible to provide sufficient gain through the hearing aid to allow audibility. Furthermore, even if sounds are made audible, the ability of the listener to use information in these frequency regions may be compromised (e.g., Ching et al. 1998; Ching et al. 2001a; Hogan & Turner 1998; Turner & Cummings 1999; Moore 2001; Vickers et al. 2001). Some hearing aid prescriptive procedures will take into account the ineffectiveness of trying to restore full audibility in the high frequencies for those with profound high frequency loss. These prescriptions recommend less gain in the higher frequencies and more gain in the low frequencies as the thresholds at 2000 Hz and above exceed 95 dB HL (e.g., Byrne et al. 1990; Byrne et al. 1991; Byrne et al. 2001; Dillon, 2006; Keidser et al. 2011). Other prescriptive procedures do not modify targets for high frequency gain (e.g., Bagatto et al. 2005; Moore et al. 2010).

Although a hearing aid amplifying only low frequencies would not be expected to yield useful speech recognition performance on its own, multiple studies have shown that speech recognition performance can improve significantly even when only low frequency acoustic information is presented in combination with the signal from the cochlear implant (e.g., Büchner et al. 2009; Zhang et al. 2010; Sheffield & Zeng 2012), and even when speech is unintelligible when listening to the acoustic signal alone (e.g., Kong et al. 2005; Zhang et al.

2010; Cullington & Zeng, 2010). One limitation of these studies is that they have focused primarily on listeners with steeply sloping hearing loss, but relatively good hearing at low frequencies.

For example, Zhang et al. (2010) carried out a systematic study to determine the minimum bandwidth of the acoustic information required by unilateral CI users to obtain bimodal benefit, i.e., significant improvements in speech recognition performance. All nine listeners had post-lingual hearing loss and all but one had a steeply sloping audiometric configuration. Thresholds in the unimplanted ear were 60 dB HL at audiometric frequencies up to and including 500 Hz and 60 dB HL at 1000 Hz and higher frequencies. In order to assess the contribution of the acoustic signal to bimodal performance, the acoustic speech stimuli were unfiltered (wideband) or low-pass (LP) filtered (LP cutoffs of 125, 250, 500 or 750 Hz). These stimuli were amplified for each subject using the frequency/gain response targets specified using the NAL-RP prescriptive formula (Byrne et al. 1991). The acoustic speech stimuli were presented through an Etymotic ER-1 earphone. Unmodified speech stimuli were sent directly to the cochlear implant via auxiliary input. Speech recognition performance was assessed in quiet using monosyllabic (CNC) words and in noise (+10 dB SNR) using the AZBio test materials (Spahr & Dorman 2004; Gifford et al. 2008; Spahr et al. 2012). Test conditions included: acoustic alone (4 bandwidths), CI alone, and CI plus acoustic (4 bandwidth conditions).

Results in quiet and in noise revealed that speech recognition performance was significantly higher in all bimodal test conditions than in the CI alone or acoustic wideband alone conditions. For CNC words administered in quiet, the CI alone condition score was 56%. Addition of the 125 Hz LP signal to the contralateral ear resulted in a bimodal score of 78%. Bimodal performance did not change significantly as the bandwidth of the acoustic signal was increased to include higher frequencies. For sentences administered in noise, again, the primary increase in speech recognition performance due to bimodal listening was derived from provision of acoustic information contained below 125 Hz. The CI alone score was 40%. Addition of the 125 Hz LP signal yielded a bimodal score of 70%. A further significant increase in bimodal score was obtained in the bimodal 750 Hz LP condition and the bimodal wideband (unfiltered acoustic) condition; scores in these conditions were 82% and 87%, respectively. Zhang et al. (2010) suggest that larger increases in bimodal benefit with increasing bandwidth might occur for listeners with better residual hearing in the mid-frequency region.

The systematic study of the effect of “hearing aid” bandwidth by Zhang et al. (2010) focused specifically on the contribution of amplification in the low-frequency region (below 750 Hz) in a population of bimodal CI users whose access to acoustic information would be best in the low-frequency region by virtue of their audiometric configuration. It is unclear whether the Zhang et al. findings can be generalized to bimodal users who have poorer low-frequency residual hearing, but who have usable residual hearing over a relatively wide frequency range. It appears likely that the ability to obtain bimodal benefit from provision of only low-frequency acoustic information may depend on the degree and configuration of hearing loss. A second factor that needs to be considered is that Zhang et al. simulated a hearing aid and presented stimuli through an earphone. The hearing aid simulation did not include the type of low frequency cut-off typical of conventional hearing aids. Essentially, a hearing aid acts as a bandpass filter. Few hearing aids have a lower-frequency cutoff below 125 Hz and typically hearing aid prescriptive procedures do not provide targets for gain at frequencies below 250 Hz. Therefore it is important to obtain information about the potential contribution of low, mid, and higher frequency acoustic information to bimodal benefit through actual hearing aids.

The contribution of mid (1000-2000 Hz) and high frequency amplification (2500 - 6000 Hz) to bimodal benefit has not been systematically investigated. Research by Mok and colleagues (2006) suggests the possibility that it might be preferable to limit the hearing aid bandwidth to provide only low frequency amplification because providing acoustic information at 1000 Hz and above might actually interfere with information being provided by the CI. They evaluated 14 experienced adults who were bimodal users. All used a unilateral CI (Nucleus 24) and their personal hearing aid which had been fit using the NAL-RP prescriptive procedure. Although subjects' unaided thresholds were not reported, aided soundfield thresholds were reported. It appears from soundfield thresholds that listeners had severe-to-profound, or profound hearing loss. Mok et al. reported that bimodal users with *poorer aided* thresholds at 1000 and 2000 Hz obtained greater bimodal benefit than users with better aided thresholds. In addition, listeners whose hearing aid did not provide amplification at 4000 Hz (due to the severity of hearing loss) obtained more benefit than those who did. Mok and colleagues interpreted these results as indicating possible negative interactions between the acoustically amplified signal at mid and high frequencies and the electrical signal from the cochlear implant. The frequency to place mapping in the auditory system is not matched between the hearing aid side and the cochlear implant ear. For those hearing aid users who do not achieve as much audibility in the mid and high-frequency regions, there is less opportunity for conflicting information from the two ears (where low frequency sounds encoded by the CI may be stimulating characteristic frequencies in the mid-frequency region while the hearing aid ear is also stimulating mid-frequency regions).

In contrast, results from studies by Ching et al. (2001b) and Ching et al. (2004b) suggest that, on average, the frequency response prescribed using the NAL prescriptive procedure will be appropriate, but that the overall gain should be adjusted in order to match the loudness of the speech heard through the hearing aid and through the cochlear implant. In both of the studies, a paired-comparison procedure was administered to determine the preferred frequency response (for speech intelligibility) among a set of hearing aid settings that systematically differed in slope from the NAL prescriptive target. In the study of performance of 16 children (Ching et al. 2001b), 12 of the 16 subjects chose a frequency response whose slope was within 3 dB of the NAL-RP target. However, there were some subjects who preferred a frequency response which differed in slope from that recommended by the NAL prescription. Three listeners chose a response with a slope that differed from the NAL target by -4 to -6 dB per octave (preferred less high frequency amplification than recommended by the NAL prescriptive procedure). One listener selected a frequency response with a low frequency boost. Eight of 16 children required 6-16 dB increases in HA gain and one child required a 6 dB decrease in HA gain to match the loudness of the CI. In the study of adult bimodal listeners with acquired profound hearing loss, Ching et al. (2004b) found that, on average, the NAL-NL1 target was appropriate. The majority of the subjects (14 of 21) preferred a frequency response whose slope was within 3 dB of the NAL-NL1 target. Three subjects preferred a frequency response with slightly greater high frequency emphasis, and four subjects preferred a frequency response with less high frequency emphasis. Again individual listeners required adjustment to the HA gain to match the loudness of the CI.

It is thus unclear whether the approach to fitting the hearing aid for bimodal listeners should be modified in order to focus on providing primarily low frequency information, or whether a wideband hearing aid fitting that would be more typical of stand-alone hearing aid use is appropriate. Research has shown that even CI users with severe-to-profound hearing loss in the contralateral ear can benefit from amplification (e.g., Ching et al. 2001b, Ching et al. 2004b, Potts et al. 2009; Mok et al. 2006), but the amount of benefit contributed specifically by low (below 500 Hz), mid (1000-2000 Hz) and high frequency amplification (2000-6000 Hz) to bimodal benefit has not been systematically investigated. The purpose of the present

study is to examine the effect of hearing aid bandwidth on bimodal speech perception in a group of bimodal listeners with severe-profound hearing loss in the unimplanted ear, but with residual hearing sufficient for wideband amplification using NAL-RP prescriptive guidelines; unaided thresholds no poorer than 95 dB HL through 2000 Hz. Speech recognition performance was measured in soundfield with the CI alone and with each of four bimodal fittings implemented in a digital behind-the ear (BTE) hearing aid. The hearing aid bandwidth was systematically changed to include a wideband setting (NAL-RP prescription), and three additional settings with narrower bandwidths with upper frequency cutoffs extending to 2000, 1000, or 500 Hz. Testing was carried out in quiet in Experiment 1 and in noise in Experiment 2.

Materials and Methods

The New York University School of Medicine Institutional Review Board approved all experimental procedures. Informed consent was obtained from each subject.

Subjects

Fourteen bimodal listeners participated in the study. All subjects had post-lingual hearing loss, used a single cochlear implant, and reported using a hearing aid daily. Subjects had severe-to-profound hearing loss, with no unaided thresholds poorer than 95 dB HL through 2000 Hz or poorer than 115 dB HL at 4000 Hz. Pure tone thresholds for participants in Experiments 1 and 2 appear in Tables 1a and 1b, respectively. Scores obtained during clinical testing indicated that speech recognition scores with the CI alone were higher than results obtained with their personal HA alone worn in the contralateral ear. The advantage of the CI ear over the HA ear was sometimes large and sometimes negligible, ranging from 4-76% for CNC monosyllabic words and from 4% to 96% for speech recognition in noise (HINT test at +10 dB SNR). However, this means that for all these subjects bimodal benefit can be calculated as the difference between the bimodal and the CI speech perception scores. The majority of subjects had additional time for testing in the laboratory, and this extra time was used to replicate the across-ear comparison observed in the clinic. The advantage of the CI ear over the HA ear was indeed confirmed for all subjects who were tested. Listener demographics are described in Tables 2a and 2b. As can be seen, all had years of experience using a HA in the unimplanted ear (range of 5.5-39 years). Experience with the CI ranged from one-half year to 8 years.

Subjects were assigned to be tested in quiet (Experiment 1) or in noise (Experiment 2) based on their speech recognition scores with the CI alone measured in the clinic. In order to avoid ceiling scores in the quiet test condition, those who scored 90 % on the Hearing in Noise Test sentences (HINT) administered at +10 dB signal-to-noise ratio (SNR) with the CI alone were assigned to be tested in noise (Experiment 2). Those with <90% score on the HINT sentences in noise (+10 dB SNR) were assigned to the quiet condition (Experiment 1). Two participants (subjects 7QN & 8QN) whose performance through the CI was close to 90% on the HINT sentences in noise were tested in both quiet and noise.

Hearing aid fitting

Although all of the participants used a hearing aid on a regular basis, the type of hearing aid worn and the method of fitting the hearing aid differed among subjects. Therefore, in order to exert systematic control over the characteristics of the hearing aid and to assure a common prescriptive procedure for all subjects, a single BTE hearing aid, the Siemens Motion 700 P, was used for testing. This hearing aid has a low frequency limit of 100 Hz and a high frequency limit of 7100 Hz. The bandwidth of the hearing aid can be adjusted by controlling the gain in each of 16 channels. The hearing aid was programmed as a linear

hearing aid (with compression used for output limiting). All additional signal processing strategies were disabled and the microphone was set to an omnidirectional response.

Four frequency responses differing in bandwidth were programmed into four memories of the hearing aid. The hearing aid was programmed using Connexx 6.4.2 software in conjunction with a Hi-Pro interface box. Program 1 was set according to the NAL-RP prescriptive procedure (Byrne et al. 1991) and is the wideband condition. Three additional programs included narrower hearing aid bandwidths with nominal upper frequency cutoffs set at 2000 Hz (Program 2), 1000 Hz (Program 3), and 500 Hz (Program 4).

The NAL-RP prescriptive procedure was used for the wideband hearing aid frequency-gain response because it is specifically designed to address the amplification needs of those with severe and profound hearing loss. This prescriptive procedure has been successfully used in previous research with bimodal users (e.g., Ching et al. 2001b, Mok et al. 2006, Zhang et al. 2010). In addition, the NAL-RP prescriptive target for average input levels (65 dB) is often similar to the target used in the NAL non-linear procedure (NAL-NL1) also used in a previous bimodal study (Ching et al. 2004b).

Since the NAL-RP prescriptive procedure does not provide target gains below 250 Hz, for the purposes of this study, the gain in the channel below 250 Hz was set as close as possible to the gain in the 250 Hz channel, while still matching the 2cc coupler target at 250 Hz. The prescribed 2cc coupler gain for the wideband (NAL-RP) setting was calculated using average real-ear-to-coupler difference values. The target frequency responses for the band-limited conditions were obtained by reducing the gain in frequency channels above the nominal cut-off frequency using the Connexx software. The hearing aid frequency/gain response was then measured in a 2 cc coupler (Fonix 6500-CX hearing aid analyzer) using a weighted broadband noise signal (65 dB SPL). The 2 cc coupler gain provided below 200 Hz was later verified using the Interacoustics Affinity 2.0 hearing aid analyzer. The gain in each of 16 channels of the hearing aid was manipulated using the Connexx software to match the prescriptive target as closely as possible. An example of the four frequency responses for one of the subjects tested in noise (S3N) appears in Figure 1.

In general, it was possible to match the NAL-RP target within 5 dB of targets through 2000 Hz. Larger deviations from target are evident for several of the subjects at 3000 and 4000 Hz. Deviations from target (dB) as a function of frequency appear in Table 3a for the subjects tested in quiet and in Table 3b for the subjects tested in noise.

Instrumentation

Testing was carried out in a double-wall, double-room IAC test suite. Speech materials stored on the computer were played through an Echo-Layla 24 sound card/multi-track recorder, test levels were controlled using a Grason Stadler GSI 61 audiometer, amplified (Crown D-75) and played through an Audax HP080M0 loudspeaker. The listener sat facing the loudspeaker at a distance of 1 meter (0° azimuth). Calibration was carried out daily at the location to be occupied by the listener's head using a Larsen Davis 800 B sound level meter with the Larsen Davis 2559 microphone.

Test materials and protocol

The listener set the CI speech processor to his/her everyday program and volume setting. The experimental hearing aid was coupled to the subject's ear either with his own earmold or with a disposable foam earmold (Microsonic #407). While continuous discourse was played through the loudspeaker (level of 65 dB SPL), the listener set the volume control of the hearing aid (set to the wideband setting) to match the loudness of speech through the cochlear implant. The loudness matching procedure recommended by Ching et al (2004a)

was used. AZBio sentence materials were used to test speech recognition performance. The AZBio sentence test was selected because it is more difficult than other sentence tests which have been used for assessing speech recognition performance of CI users in quiet and in noise (Gifford et al. 2008). We chose to use sentences rather than monosyllabic words to assess speech recognition performance. The frequency-importance function for sentences is different than that for monosyllabic words; compared to words, sentences contain information that is carried disproportionately by low and mid-frequencies (Studebaker, Pavlovic & Sherbecoe, 1987). These materials may therefore be more sensitive to assessing the contribution of low and mid-frequency acoustic information delivered by the hearing aid to a bimodal listener.

Five practice sentences preceded each test condition. One AZBio list was administered per test condition. Subjects listened to and repeated each sentence. The examiner scored the number of words correct. The speech presentation level was 65 dB SPL. For the group tested in noise, the speech and the AzBio babble were presented from the same loudspeaker. The presentation level of the noise was 55 dB SPL (+10 dB SNR). Test conditions (CI alone, Bimodal 500 Hz, Bimodal 1000 Hz, Bimodal 2000 Hz and Bimodal wideband) were assessed in random order.

Approach to data analysis

Separate analyses were carried out for the quiet and the noise conditions. Speech recognition data were analyzed on a group and on an individual basis. For analysis of group data, speech recognition scores (proportions) were converted to arcsine units in order to stabilize the error variance and were then analyzed using a repeated measures analysis of variance (RMANOVA). The Tukey Honestly Significant Difference (HSD) test was used for post hoc analysis. Scores of individual listeners were compared using the 95% confidence intervals for the AZBio test material (Spahr et al. 2012).

Results

For the group of subjects tested in quiet, speech recognition performance was found to differ significantly as a function of listening condition ($F_{4,28} = 6.66$, $p < 0.001$). Tukey HSD post hoc analysis revealed that the mean scores for the Bimodal 2000 Hz and the Bimodal wideband condition were significantly higher than the mean CI alone score ($p < 0.05$), but did not differ significantly from each other. The mean performance in the Bimodal 500 Hz and Bimodal 1000 Hz conditions did not differ significantly from mean performance with the CI alone ($p > 0.05$).

For the group of subjects tested in noise, again speech recognition performance was found to differ significantly as a function of listening condition ($F_{4,28} = 3.46$, $p < 0.05$). The Tukey HSD post hoc analysis revealed that of the bimodal conditions, only the Bimodal 2000 Hz and Bimodal wideband conditions were significantly higher than the mean CI alone score ($p < 0.05$). The mean Bimodal 2000 Hz and wideband scores did not differ significantly from each other. Mean performance in the Bimodal 500 Hz and 1000 Hz conditions did not differ significantly from mean performance with CI alone ($p > 0.05$).

Individual speech recognition scores on the AZBio test and group mean scores are shown for subjects tested in quiet in Figure 2 and for the subjects tested in noise in Figure 3. Bimodal scores that differ significantly from the CI alone score for each individual subject or for the whole group ($p < 0.05$) are indicated with asterisks. In the quiet test condition, five subjects (S1Q, S2Q, S6Q, S7QN and S8QN) had significantly higher scores with one or more of the bimodal fittings than in the CI alone condition, while three of the subjects (S3Q, S4Q and S5Q) did not show bimodal benefit. Only S5Q showed a significantly lower score

in a bimodal condition than in the CI alone condition, and that happened only in one condition (Bimodal 1000 Hz). In the noise condition, five subjects (S2N, S3N, S5N, S7QN, and S8QN) had significantly higher scores with one or more of the bimodal fittings than in the CI alone condition. Three subjects (S1N, S4N, and S6N) failed to show bimodal benefit on the AZBio in noise task. As can be seen, there are individual differences in the minimum bandwidth yielding bimodal benefit. For two of the subjects (S3N and S8QN), the minimum hearing aid bandwidth yielding bimodal benefit was 500 Hz. For two subjects (S6Q and S2N), the minimum bandwidth yielding bimodal benefit was 1000 Hz. For three subjects, the 2000 Hz bandwidth was required for bimodal benefit. For two subjects (S7Q and S5N), the wideband fitting was required to obtain bimodal benefit.

Two of the subjects (S7QN and S8QN) were tested in both quiet and noise conditions. For S7QN, the wideband hearing aid setting was optimal in quiet, while the 2000 Hz bandwidth was optimal in noise. For subject S8QN, the 2000 Hz bandwidth gave optimal bimodal benefit in quiet, whereas in noise even the 500 Hz hearing aid bandwidth yielded significant improvement over listening with the CI alone.

Discussion

Performance of the subjects on the AZBio test materials can be compared to performance on the AZBio test materials reported in the literature. Mean performance with the CI alone in quiet (64.5%) is similar to mean scores of 69% reported by Spahr et al. (2012) and by Gifford et al. (2007). The mean bimodal (wideband) score in quiet of 77.8% is also similar to the mean bimodal score of 83% reported by Gifford et al. (2007) for listeners with thresholds 60 dB HL below 500 Hz and thresholds 80 dB HL at 2000 Hz.

Mean performance with the CI alone on the AZBio test material in noise was 70.6%. This score is much higher than the mean of 40% for CI alone performance on the AZBio in noise (same SNR) reported by Zhang et al. (2010) and of 39% reported by Gifford et al. (2007). The higher performance on the AZBio test material in noise by the CI users in the present study would be expected, since subjects were assigned to the noise condition based on excellent CI alone performance (scores 90%) on the HINT sentences (10 dB SNR). The mean bimodal (wideband) performance by listeners in the current study was 80.9%. This score is similar to the bimodal score of 87% reported by Zhang et al. (2010), but is higher than the mean score of 62% obtained by the bimodal subjects tested by Gifford et al. (2007).

On average, bimodal speech recognition was significantly higher than CI alone performance in both quiet and in noise conditions when hearing aids provided amplification in both the low and mid-frequency regions (through 2000 Hz). Performance did not increase further as the bandwidth was extended to the higher frequencies. The hearing aid bandwidths extending to 500 or 1000 Hz did not result in bimodal benefit. Results from an earlier study by Zhang et al. (2010) in which the bandwidth of the acoustic signal was manipulated demonstrated that the provision of low frequency (below 125 Hz) information in the ear contralateral to the CI resulted in substantial increases in speech recognition performance (Zhang et al. 2010). There are some important methodological differences between Zhang et al. and the present study that might explain the apparent difference in the findings. One such difference is our use of an actual hearing aid for testing. Zhang et al. (2010) simulated a hearing aid (NAL-RP frequency response) and presented filtered speech through the "hearing aid" via an insert earphone. The low-pass filtered speech signal thus contained information below 125 Hz. In the present study, a digital hearing aid was used to implement the NAL-RP fitting. The hearing aid bandwidth does not extend below 100 Hz. Testing was carried out in soundfield through a loudspeaker whose frequency response is flat between 200 and 6500 Hz but drops by approximately 8 dB from 200 to 100 Hz, so the speech

received through the combined loudspeaker/hearing aid provided less acoustic information at frequencies below 200 Hz than the earphone used in the Zhang et al. (2010) study. This attenuation of frequencies below 200 Hz is typical of many hearing aid frequency responses. It should be pointed out that in general, hearing aid prescriptive procedures do not prescribe gain at frequencies below 200 Hz. Although hearing aid users with only a mild hearing loss in the low frequencies would most probably be provided with a hearing aid with venting, thus allowing direct access to low frequency acoustic information, those with more substantial hearing loss would be dependent on the amplification provided through the hearing aid at low frequencies. Furthermore, little gain is provided in low frequencies by the NAL-RP prescription. It is possible that an alternate prescriptive procedure which provides more low frequency gain might have provided our listeners with more access to low frequency information, or alternatively, if we had increased the volume control of the hearing aid as the bandwidth was decreased, listeners might have had more access to low frequency acoustic information.

It is also likely that differences in the amount of residual hearing of subjects in the two studies may account for the differences in the ability of the subjects to use low, mid and higher frequency information delivered through the hearing aid. Whereas the subjects in the Zhang et al. (2010) study had relatively good hearing at low frequencies (thresholds of 20 – 40 dB HL at 125 Hz, 25-45 dB HL at 250 Hz, and from 35-60 dB HL at 500 Hz) and generally had steeply sloping sensorineural hearing loss, the majority of the participants in the present study have poorer low frequency hearing and better mid and high-frequency hearing than those studied by Zhang et al. (2010).

Previous research suggests that the ability to use low frequency auditory information may be different for persons with steeply sloping audiograms than for those with flatter audiometric configurations or more gradual audiometric slopes. For example, listeners with steeply sloping losses have been shown to obtain better speech recognition scores from low-pass filtered speech than listeners with similar low frequency loss, but better high frequency thresholds (Hornsby et al. 2011). Boothroyd (1967) provided evidence that some listeners with relatively normal low frequency hearing and steeply sloping sensorineural hearing loss were better able to use low frequency information in low-pass filtered speech than were listeners with normal hearing. For the listeners with good low-frequency hearing in the Zhang et al. (2010) study, it is possible that extended experience with listening to speech that was “low-pass” filtered due to the configuration of hearing loss and relatively less audibility of mid and high frequency information through the hearing aid would result in greater ability to extract information from low-pass filtered speech. In contrast, the subjects in our study have sufficient hearing at higher frequencies to allow access to mid-and high frequency speech information. They are also accustomed to receiving this information through their hearing aids. This could make access to only low-frequency information inadequate for bimodal benefit.

Our findings do not support the suggestion by Mok et al. (2006) that provision of mid-frequency amplification might be deleterious to bimodal benefit. In fact, amplification of the mid-frequency region was necessary for obtaining bimodal benefit. This finding is in agreement with data reported by Potts et al. (2009) supporting the importance of providing amplification to the mid-frequencies in hearing aids used for bimodal fittings.

Research by Ching and colleagues (Ching et al. 2001b, Ching et al. 2004b) suggested that while the NAL prescription was appropriate for bimodal fittings of many listeners, individual listeners might require a frequency response somewhat different than that recommended by the NAL prescription. Individual subject data were examined to determine whether significant differences in bandwidth requirements could be detected using a single

test list of the AZBio test materials per condition, as would typically be used in a clinical evaluation. The 95% confidence intervals developed by Spahr et al. (2012) were used to determine significant differences. For the majority of the subjects tested, speech recognition performance was significantly better in one or more of the bimodal test conditions than when listening only with the cochlear implant, and in most cases benefit in bimodal conditions occurred for hearing aid bandwidths providing amplification that, at minimum, included the low- and mid-frequency region. Several of the subjects did show bimodal benefit when the hearing aid was set to amplify primarily low frequencies. There were individual subjects who did not show statistically significant bimodal benefit in any of the test conditions. It is possible that if more test lists had been used per condition that it would have increased the possibility of detecting differences among the test conditions. Subjects S1N, S4N and S3Q all started out with scores of 80% or higher with the CI alone. This made it difficult to show significant improvements in bimodal test conditions. It might have been advisable to use a poorer signal-to-noise ratio (+5 dB) for these subjects tested in noise and to test S3Q in noise rather than in quiet.

It is also likely in several of the cases, that the hearing aid actually did not provide bimodal benefit. For example, S4Q reported that he used his HA along with the CI because he had difficulty understanding speech using only the CI. However, he did not feel that the hearing aid helped him very much and he was looking into the possibility of receiving a second CI. His speech recognition performance on the AZBio sentences with the WB hearing aid alone was 0%. A follow up with S1N revealed that she had discontinued using her hearing aid within months of being tested because she found that “the hearing aid increased the sound level, but did not increase clarity of speech.” S4N reported that she receives minimal help from the hearing aid in understanding speech when she uses the CI, but that she feels that wearing the hearing aid helps her localize non-speech sounds.

It is puzzling that S5Q failed to show bimodal benefit. His AZBio score with the WB hearing aid alone was 33% (14% when listening with his personal hearing aid) and his CI alone performance (54%) leaves sufficient room for improvement. He is one of the subjects with only 6 months experience with the CI and it is possible that bimodal performance will improve over time.

Conclusions

Speech recognition performance was measured with the CI alone and in combination with hearing aid fittings differing in bandwidth to determine the contribution of acoustic amplification of low (below 500Hz), mid (1000-2000 Hz) and high frequency regions (above 2000 Hz) to bimodal benefit. Bimodal listeners had severe to profound sensorineural hearing loss with residual hearing through 4000 Hz (thresholds no poorer than 95 dB HL at audiometric frequencies 250-2000 Hz, and no poorer than 115 dB at 4000 Hz). On average, the hearing aid response extending to 2000 Hz was the minimum bandwidth required for bimodal benefit both in quiet and in noise. These findings indicate that for listeners with this type of hearing loss, access to mid and higher frequency information from the hearing aid is necessary for bimodal benefit. The hearing aid should provide acoustic information at all frequencies with usable residual hearing. The small number of subjects tested and the use of a single test list limit our ability to look for patterns related to audiometric or demographic factors that would predict required bandwidth or changes in the frequency-gain response requirements for the HA being used in conjunction with a CI for individual listeners. Future research will focus on larger numbers of bimodal users with differing degree and configuration of residual hearing to determine whether there are systematic differences in the hearing aid fitting required for bimodal patients based on characteristics of their residual hearing.

Acknowledgments

Research was supported by Grant No. 1R01DC011329 from NIH/NIDCD.

Siemens Hearing Instruments provided the hearing aid used for the study.

We are grateful to Susan Waltzman, William Shapiro, and the audiologists at the New York University Cochlear Implant Center for assistance with subject recruitment efforts. Keena Seward prepared the figures for the manuscript.

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Summary

The purpose of this study was to determine how the bandwidth of the hearing aid (HA) affects bimodal speech recognition of listeners with a cochlear implant (CI) in one ear and severe-to-profound sensorineural hearing loss in the aided, unimplanted ear. Speech recognition performance was measured with CI alone and in combination with hearing aid fittings differing in bandwidth. Significant bimodal benefit was obtained when the hearing aid provided amplification at all frequencies with aidable residual hearing. Limiting amplification to only low frequencies (below 1000 Hz) did not yield significant improvements in performance over listening with the CI alone.

Figure 1.
The four frequency/gain responses programmed for one of the subjects tested in noise (S3N). Measurements were obtained in a 2cc coupler using a weighted broadband noise signal (65 dB input).

Figure 2.

Speech recognition performance on the AZBio test with the CI alone and in four bimodal conditions (HA upper frequencies set to 500, 1000, 2000 Hz or wideband). Asterisks above individual subject data indicate a significant difference from the CI alone score ($p < .05$). Asterisks above the mean data indicate a significant difference from the CI alone score based on the results from the RMANOVA.

Figure 3.

Speech recognition performance in noise (+10 dB SNR) on the AZBio test with the CI alone and in four bimodal conditions (HA upper frequencies set to 500, 1000, 2000 Hz or wideband). Asterisks above individual subject data indicate a significant difference from the CI alone score ($p < .05$). Asterisks above the mean data indicate a significant difference from the CI alone score based on the results from the RMANOVA.

Audiometric thresholds (dB HL) of the unimplanted ear of subjects tested in Experiment 1 (quiet condition)

Table 1a

	Audiometric Thresholds (dB HL) as a function of frequency (Hz)						Average	Average
	250	500	1,000	2,000	4,000	8,000	.5, 1k, & 2kHz	.25 and .5kHz
S1Q	75	75	75	70	65	30	73.33	75.00
S2Q	60	65	85	80	90	85	76.67	62.50
S3Q	55	65	70	80	80	95	71.67	60.00
S4Q	60	80	95	95	95	95	90.00	70.00
S5Q	95	85	80	75	85	NR	80.00	90.00
S6Q	70	65	70	80	115	NR	71.67	67.50
S7QN	35	50	85	85	95	NR	73.33	42.50
S8QN	55	65	70	95	110	90	76.67	60.00
Mean	63.13	68.75	78.75	82.50	91.88		76.67	65.94

Table 1b

Audiometric thresholds (dB HL) of the unimplanted ear of subjects tested in Experiment 2 (noise condition)

	Audiometric Thresholds (dB HL) as a function of frequency (Hz)						Average .5, 1k, & 2kHz	Average .25 and .5kHz
	250	500	1,000	2,000	4,000	8,000		
S1N	50	50	75	90	90	90	71.67	50.00
S2N	70	75	85	95	95	95	85.00	72.50
S3N	80	85	100	90	75	NR	91.67	82.50
S4N	70	70	80	80	95	NR	76.67	70.00
S5N	65	75	100	90	85	95	88.33	70.00
S6N	65	75	80	75	70	95	76.67	70.00
S7QN	35	50	85	85	95	110	73.33	42.50
S8QN	55	65	70	95	110	85	76.67	60.00
Mean	61.25	68.13	84.38	87.50	89.38		80.00	64.69

Table 2a

Demographic information for participants in Experiment 1 (quiet)

S	Age (yrs)	Etiology HL	Duration HL (yrs)	HA Experience (yrs)	Current Hearing Aid	CI Experience (yrs)	CI internal device CI speech processor
S1Q	63	unknown	39	39	Oticon Digifocus	1	AB Hi-Res 90k Harmony HiRes-S, HiFidelity 120
S2Q	62	Usher's syndrome	49	39	Phonak Supero	0.5	Coch-CI512, Freedom/ACE
S3Q	73	middle ear pathology	45	35	Siemens ITE	1.5	Coch-CI24RCA, Freedom/ACE
S4Q	50	unknown	9	8	Oticon Personal BTE	2.75	AB Hi-Res 90k, Harmony HiRes-S, Fidelity 120
S5Q	62	noise exposure	42	12	Microtech Radius 12	1	AB Hi-Res 90k, Harmony HiRes-P, Fidelity 120
S6Q	67	unknown	35	23	Siemens Intuis SP	1.5	AB-Hi-Res 90k, Harmony HiRes-S, Fidelity 120
S7QN	63	otosclerosis	40	28	Phonak Naïda BTE	4.5	Coch-CI24RCA, Freedom/ACE
S8QN	80	noise exposure	28	24	Widex Mx19 BTE	2	Coch-CI24RCA, Freedom/ACE
Mean	65.22		36.8	28.5		2.31	

Table 2b

Demographic information for participants in Experiment 2 (noise)

S	Age (yrs)	Etiology HL	Duration HL (yrs)	HA Experience (yrs)	Current Hearing Aid	CI Experience (yrs)	CI internal device CI speech processor
S1N	55	genetic	22	18	Widex Inteo	3	Coch-CI24RCA, Freedom/ACE
S2N	67	noise exposure	38	33	Phonak Savia Art BTE	6	Coch-CI24RCA, Freedom/ACE
S3N	65	otosclerosis	48	24	Phonak B6	8	Medel Combi 40+ Opus2/FSP
S4N	72	unknown	15	5.5	Widex Inteo	3.5	Coch-CI 24RCA, Freedom/ACE
S5N	40	Usher's syndrome	34	34	Phonak Naida V UP BTE	1	AB 90K, Harmony HiResP Fidelity 120
S6N	64	Usher's syndrome	22	12	Phonak Naida Exeila P	1	Coch-CI512, Freedom/ACE
S7QN	63	otosclerosis	40	28	Phonak Naida BTE	4.5	Coch-CI24RCA, Freedom/ACE
S8QN	80	noise exposure	28	24	Widex Mx19 BTE	2	Coch-CI24RCA, Freedom/ACE
Mean	63.25		30.67	24.83		3.63	

Table 3a

Deviation from 2 cc target gain in dB as a function of frequency. Experiment 1

	Frequency (Hz)					
	250	500	1000	2000	3000	4000
S1Q	0	-2	-1	-3	-4	-1
S2Q	5	3	0	3	-7	-10
S3Q	0	2	5	5	-3	-6
S4Q	-5	2	3	5	-13	-10
S5Q	0	-2	0	5	-15	-10
S6Q	0	0	5	5	-9	-13
S7QN	-5	0	0	0	-5	-10
S8QN	0	5	8	10	-5	-10

Table 3b
Deviation from 2 cc target gain in dB as a function of frequency. Experiment 2

	Frequency (Hz)					
	250	500	1000	2000	3000	4000
S1N	0	5	3	2	-8	-8
S2N	0	0	-2	-5	-10	-20
S3N	3	7	3	5	-7	-10
S4N	6	7	7	6	0	-8
S5N	2	4	0	0	-10	-18
S6N	0	5	10	12	0	-5
S7QN	-5	0	0	0	-5	-10
S8QN	0	5	8	10	0	-10