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A Sound Foundation Through Early Amplification

Proceedings of the 7th International Conference 2016

Optimizing outcomes with pediatric bimodal hearing: effect of acoustic bandwidth

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Abstract

The primary purpose of this study was to examine the effect of acoustic bandwidth on bimodal benefit for speech understanding in pediatric cochlear implant (CI) recipients. Eleven children (6 to 13 years) with cochlear implants utilizing a bimodal hearing configuration participated in this study. Speech understanding was assessed via recorded sentences presented in a 20-talker babble. The Pediatric AzBio sentences were used for all conditions. The CI stimulus was always unprocessed and the low-pass filtered stimuli were delivered to the non-CI ear with the following cutoff frequencies: 250, 500, 750, 1000, and 1500 Hz.
The primary findings were that children 1) gained significant bimodal benefit with just 250 Hz;2) demonstrated no additional bimodal benefit with increasing acoustic bandwidth; and 3) the degree of bimodal benefit for each low-pass filter was not related to the audiometric threshold at that frequency.
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Acoustic bandwidth effects for pediatric CI recipients were significantly different than those documented in the literature for adult CI recipients. Specifically, pediatric CI recipients show no further increases in bimodal benefit with acoustic bandwidth, primarily consistent with a segregation theory of bimodal integration. Further work is needed in this

area to define data-driven guidelines for determining bilateral implant candidacy versus those who would best be served with a bimodal hearing configuration.

Introduction

Research has shown that modern cochlear implant (CI) recipients are routinely achieving open-set word recognition in the range of 60 to 70% for unilaterally implanted ears (Davidson, Geers & Brenner, 2010; Gifford et al., 2014). Despite this success, a considerable number of CI recipients receive minimal benefit, and several aspects of hearing (including speech understanding in noise, music perception, and music appreciation) remain challenging for even the best performers. Many attribute these difficulties with speech understanding in noise and music-based activities as being related to poor spectral resolution (e.g., Henry & Turner, 2003; Henry, Turner & Behrens 2005; Litvak, Spahr, Saoji & Fridman, 2007), which is generally attributed to a number of factors including: 1) discrete number of independent intracochlear electrodes; 2) loss of temporal fine structure associated with envelope-based signal processing strategies; and 3) intracochlear current spread, more commonly referred to as channel interaction. Common ways to improve speech understanding in noise for CI recipients include; signal preprocessing strategies designed to enhance speech and/or reduce noise in adverse listening environments; use of remote microphones including wireless and digitally modulated (DM) or frequency modulated (FM) technology;, as well as induction loops and an integrated telecoil. Another option, however, relates to the clinically recommended intervention for the individual with hearing loss particularly combining the CI with a hearing aid in the non-CI ear for bimodal hearing, or a second CI.

Bimodal hearing versus bilateral implant candidacy

Since the initial approval of multi-channel CIs for children in 1990, the Food and Drug Administration (FDA) labeled indications for cochlear implantation have significantly expanded, allowing individuals with more residual hearing in the implanted and non-implanted ears to receive a CI. We know that combining residual acoustic hearing in the non-CI ear provides significant benefit for speech recognition in both adults and children (e.g., Gifford, Dorman, Sheffield, Teece, Olund & Gifford, 2014; Schafer, Amlani, Paiva, Nozari & Verret, 2011; Zhang, 2014). We also know that bilateral CIs provide significant benefit for speech understanding in quiet and in complex listening environments (e.g., Boons et al., 2012; Sheffield, Haynes, Wanna, Labadie & Gifford, 2015). Given the widespread availability of bilateral acoustic hearing in the preoperative period for a large proportion of current CI candidates, two viable treatment plans have routinely become available to unilateral CI listeners: 1) pursuit of a second CI; or 2) continued use of a hearing aid (HA) in the non-CI ear. The difficult decision of which treatment plan to pursue is complicated by the lack of established diagnostic criteria for determining bilateral implant candidacy. Indeed, there are no data-driven recommendations for determining bilateral implant candidacy over retaining a bimodal hearing configuration.

Pursuit of a second implant is particularly time sensitive in children due to critical periods of auditory, speech, and language development. Unfortunately, it is often difficult to obtain behavioral measurements of HA benefit in the non-CI ear in young children. Thus, pursuit of a second CI might be delayed and result in poorer bilateral outcomes, including significant aural preference syndrome (e.g., Gordon, Henkin & Kral, 2015), without data-driven recommendations. Thus, it is important to investigate the degree of bimodal hearing benefit derived by pediatric CI recipients systematically, so we can begin to develop data-driven guidelines for bilateral implant candidacy.

Bimodal integration theory

Currently, the two primary theories underlying bimodal benefit or bimodal integration include segregation and glimpsing. The theory behind segregation is that periodicity cues in the low-frequency acoustic stimulus (i.e., F_0) allow the listener to compare the electric and acoustic stimuli and better separate the target speech from the background noise (e.g., Kong, Stickney & Zeng, 2005; Qin & Oxenham, 2006). The theory behind glimpsing is that the spectral-dependent signal-to-noise ratio (SNR) varies over time, and that various cues of the target signal can be "glimpsed" during temporal troughs in spectral bands and/or temporal dips of the background noise (e.g., Kong & Carolyn 2007; Li & Loizou, 2008; Brown & Bacon 2009a).

Research has shown that very little acoustic hearing is required for bimodal benefit. Indeed, significant bimodal benefit is observed with acoustic bandwidths as narrow as 125 to 250 Hz for adult listeners (e.g., Brown & Bacon, 2010; Zhang, Dorman & Spahr, 2010; Sheffield & Gifford, 2014). Recently, Sheffield and colleagues investigated the effect of acoustic bandwidth in a bimodal hearing configuration for children with normal hearing listening to CI simulations (Sheffield, Simha, Jahn & Gifford, 2016). They hypothesized that children would require a broader acoustic bandwidth for maximum bimodal benefit than that for adult listeners. This hypothesis was based on research completed with children with normal hearing and hearing loss who had required broader acoustic benefit than hearing-matched adults for rapid word learning and speech understanding (e.g., Stelmachowicz, Pittman, Hoover, Lewis & Moeller, 2004, Stelmachowicz, Lewis, Choi, & Hoover, 2007; Pittman, Lewis, Hoover and Stelmachowicz, 2005). The results reported by Sheffield et al. (2016) demonstrated that: 1) adults and children with normal hearing performed similarly in all the simulated CI and bimodal conditions; 2) children derived significant bimodal benefit with the addition of low-pass filtered speech at 250 Hz; and 3) unlike previous research completed with adult CI recipients, adults and children with normal hearing gained significant additional bimodal benefit with increasing acoustic bandwidth through 1500 Hz. Of course, the participants with normal hearing listening to CI simulations had normal spectral resolution, which is not the case with typical CI recipients listening in a bimodal hearing configuration. Thus, further research in pediatric CI recipients is warranted and the primary motivation for the current study.

This report describes our ongoing research efforts aimed at defining the acoustic bandwidth needed for optimal bimodal benefit for pediatric CI recipients. Our primary hypothesis was that children with CIs would require wider acoustic bandwidth for maximum bimodal benefit than has been observed with adult bimodal listeners as well as children with normal hearing listening to CI simulations.

Participants

Eleven children with prelingual onset of deafness were recruited and consented to participate in accordance with Vanderbilt University Institutional Review Board approval. Each child was an active bimodal listener with at least nine months experience with their implant (mean = 3.3 years). Each participant had low-frequency acoustic hearing in the non-implanted ear with pure-tone thresholds ≤ 80 dB HL at or below 500 Hz. These criteria were chosen to ensure that each participant had aidable hearing below 500 Hz (loosely based on a half-gain rule and to be consistent with our previous study completed with adult bimodal listeners). Individual and mean audiometric thresholds for the non-CI ear are shown in Figure 1. Additional demographic data including age at implantation, age at study enrollment, implanted device, external sound processor, SNR used for assessment, and gender are shown in Table 1.

Speech stimuli and test conditions

Sentence recognition in noise was assessed using the Pediatric AzBio sentence lists (Spahr et al., 2014). These sentences (commonly termed "BabyBio" sentences) were presented in the cochlear implant alone (CI alone) and bimodal conditions. A 20-talker babble was used as the distracter and the signal-to-noise ratio (SNR) was chosen individually to achieve approximately 50 to 60% correct in the CI alone condition. Mean SNR was -4 dB with a range of -8 to +2 dB. Pediatric AzBio sentence lists used for each participant were randomized across listening and acoustic filter conditions.

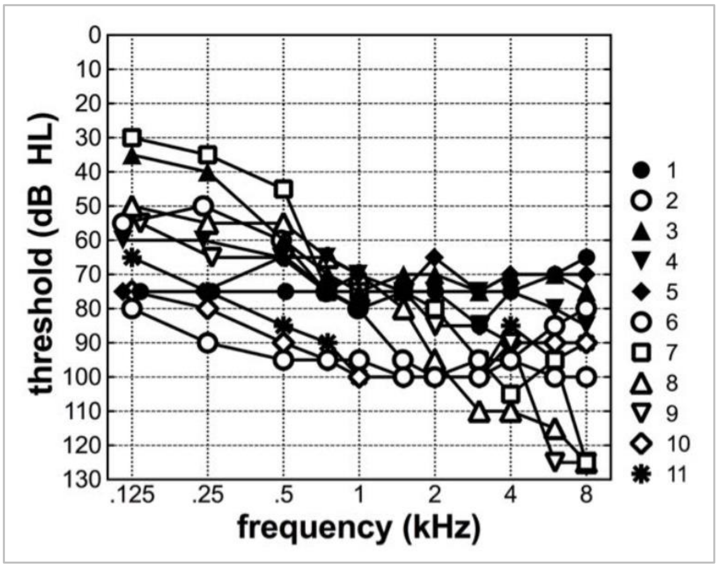

Figure 1. Individual and mean audiometric thresholds of the non-CI ear of bimodal listeners.

The CI signal was always unprocessed. The acoustic signal presented to the non-CI ear was presented in an unprocessed (wide-band) condition as well as in various low-pass filtered conditions (<250, <500, <750, <1000 Hz, <1500 Hz, and wideband). These filter bands were chosen to replicate conditions included in previous studies with adult bimodal listeners (Zhang et al., 2010; Sheffield & Gifford, 2014). We chose to eliminate the <125 Hz condition for this population given that this condition did not yield significant improvement for adult bimodal listeners. All stimuli were processed and delivered via MATLAB version 2013.

Signal processing and presentation

Filtering was implemented using MATLAB version 2013 software with a finite impulse response filter with a specific order (256, 512 or 1,024) for each filter to achieve a 90-dB/octave rolloff in each band. The BabyBio sentences and multitalker babble signals were mixed at the appropriate SNR prior to filtering.

Participant label	Gender	Age at testing	Age at implantation	Device and sound processor	SNR used for testing
1	female	7.830555556	5.769444444	Nucleus CI512, CP810	2
2	male	11.40555556	10.58888889	AB HiRes90k 1j, Harmony	**1**
3	female	7.755555556	4.333333333	AB HiRes90k 1j, Harmony	**0**
4	female	6.858333333	6.358333333	Nucleus CI422, CP810	**5**
5	female	8.416666667	5.769444444	Nucleus CI512, CP810	**-5**
6	female	9.580555556	2.080555556	AB HiRes90k 1j, Harmony	**0**
7	female	7.452777778	1.277777778	Nucleus CI24RE(CA), CP810	**-8**
8	female	13.24722222	10.66111111	Nucleus CI512, CP810	**-3**
9	male	11.15833333	10.42777778	AB HiRes90k 1j, Harmony	**-3**
10	male	8.219444444	4.736111111	Nucleus CI512, CP810	**2**
11	female	12.98055556	6.411111111	Nucleus CI24RE(CA), CP910	**-8**

Table 1: Individual participant gender, age at testing, age at implantation, implanted device and external sound processor, as well as SNR used for assessment.

CI signal delivery was achieved via direct audio input using the processor-specific personal audio cable. Testing was completed in the participants' preferred "everyday" listening program. The input CI volume level was adjusted to an individually determined comfortable listening level for each participant. Acoustic signal delivery was achieved via an ER-1 insert earphone to the nonimplanted ear. Frequency-specific gain was applied to the acoustic stimuli according to the frequency gain prescription for a 65-dB SPL input dictated by DSL v5 child targets (Scollie et al., 2005). In other words, linear gain was applied using the gain prescription defined by DSL v5 (child targets). The output of the acoustic stimuli for each low-pass band was verified to match DSL v5 child targets for a 65-dB SPL input measured via probe microphone in a Knowles Electronics Manikin for Acoustic Research (KEMAR) with the ER-1 insert earphone to verify audibility prior to each trial.

We attempted to match the CI and acoustic signals by asking each participant to indicate whether the perceived loudness of the acoustic stimulus was less than or equal to that of the CI stimulus. All participants indicated that the acoustic stimulus was equal to or greater than the CI, and thus no adjustments were made. This procedure was completed using the wide-band/unprocessed acoustic signal. Although we acknowledge that this method might have rendered a "softer" loudness perception for narrower band, acoustic stimuli, we determined this to be the cleanest experimental control for the following reasons: 1) as determined in pilot testing, the gain required to achieve balanced loudness with the narrowest band would have exceeded the limits of the equipment for the narrowest band; and 2) the output for individual low-pass filtered conditions would have been inconsistent thereby limiting comparison of bimodal benefit for a clinical population.

Analysis

A sample-size justification was completed for an analysis of variance with two listening conditions (CI alone and bimodal). The difference in means and the standard deviation used in the sample size estimate were obtained from the data of both Sheffield and Gifford (2014) and Sheffield et al. (2016) due to the similarity in methods and scope of study. Our analysis determined that a minimum sample size of 10 would be required using an α-value of 0.05 and a power of 80%. Analyses were planned and completed using repeated-measure ANOVA. For analyses regarding degree of bimodal benefit, we calculated both the percentage-point difference between bimodal and CI alone as well as normalized benefit, which takes into account the percent-based improvement between the bimodal and maximum possible score (i.e., 100% correct).

Results and discussion

Figure 2 shows mean BabyBio sentence recognition, in percent correct, for the CI alone condition (black bar) and the various bimodal conditions (grey bars). Error bars represent +1 standard error. Bimodal benefit increased with acoustic bandwidth such that there was a significant effect of condition, $F(6,10) = 10.43$, $p < 0.00$. Post hoc testing (Holm-Sidak) revealed that all bimodal conditions were significantly better than the CI alone condition ($p < 0.01$ in all cases). Furthermore, none of the bimodal conditions were found to be significantly different from one another ($p > 0.90$ in all cases). Thus, the trends seen in the current dataset are not consistent with the adult data (e.g., Zhang et al., 2010; Sheffield & Gifford, 2014) nor are they consistent with normal-hearing listeners of a similar age group listening to CI simulations.

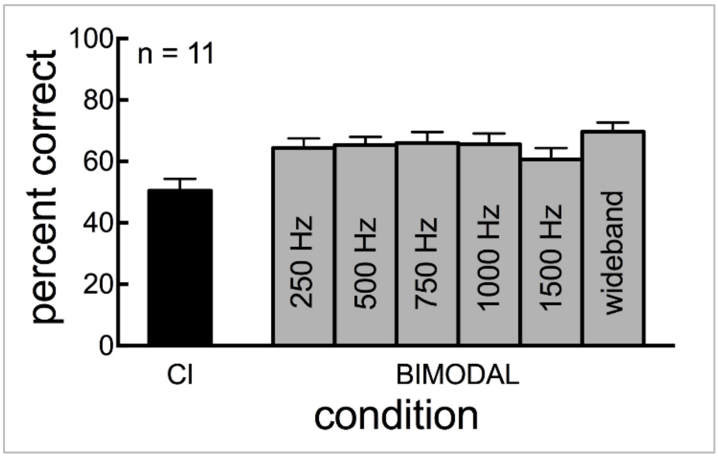

Figure 2. Mean BabyBio sentence recognition, in percent correct, for the CI alone condition (black bar) and the various bimodal conditions (grey bars). Error bars represent +1 standard error.

These data are also not consistent with our hypotheses that children would require a wider acoustic bandwidth than adults for maximum bimodal benefit and that bimodal benefit would increase with increasing bandwidth.

Figure 3 displays the degree of normalized benefit as a function of audiometric thresholds for each participant and frequency through 1500 Hz. Individual regression analyses were completed for each frequency. There was no relationship between the degree of bimodal benefit for a particular low-pass filter cutoff and the underlying audiometric threshold for that frequency ($p > 0.33$ in all cases).

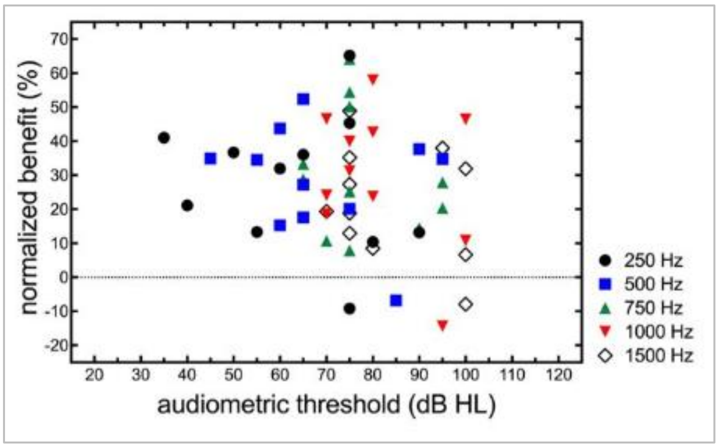

Figure 3. The degree of normalized benefit as a function of audiometric thresholds for each participant and frequency through 1500 Hz.

Conclusion

Significant bimodal benefit was observed with just 250 Hz of acoustic hearing in the non- CI ear for children listening to CI simulations. No further increases in bimodal benefit were observed for the addition of acoustic hearing beyond the 250-Hz filter. These results are different from those observed with adult CI recipients who reach a bimodal asymptote in the 500 to 750-Hz range (Zhang et al., 2010; Sheffield & Gifford, 2014) but who also generally exhibit further increases in performance, albeit not statistically significant, with acoustic bandwidth.

The current data suggest that pediatric CI recipients might benefit from minimal acoustic hearing (<250 Hz) in the non-implanted ear. This would be consistent with the segregation theory of bimodal benefit that postulates that cues in the low-frequency acoustic stimulus (including F0) allow the listener to compare the electric and acoustic stimuli and better separate the target speech from the background noise (e.g., Kong et al., 2005; Chang et al. 2006; Qin & Oxenham, 2006). Further investigation is ongoing to study the effects of SNR and degree of audibility for each of the low-pass filtered conditions to ensure that widening the acoustic bandwidth actually resulted in additive audibility for each of the conditions.

First, the SNR required to drive CI-alone performance down to approximately 50% ranged from -8 to +2 dB with a mean SNR of -4 dB. Though Sheffield and Gifford (2014) found no effect of SNR on either the magnitude or the increase in bimodal benefit with bandwidth, they only studied SNRs as low as 0 dB. Thus, it is possible that the use of negative SNRs in the current dataset impacted the listeners' ability to make use of broader acoustic bandwidths, thereby rendering only F_0 useful for bimodal integration. Second, given the sloping nature of some of the hearing losses, it is possible that not all children experienced similar increases in audibility with increased bandwidth. We are actively investigating this possibility and will proceed with further experimentation to understand bimodal integration in pediatric CI recipients.

In conclusion, predicting bimodal benefit in a pediatric CI recipient would be greatly beneficial in the clinic to guide recommendations for hearing aid use or for the recommendation of a second CI. This is especially true for our youngest CI recipients who are not yet able to participate in speech perception testing. In the meantime, any unilateral CI listener with aidable residual hearing in the non-CI ear at or above 250 Hz will likely derive benefit from amplification in the non-CI ear. However, if a child has only limited acoustic hearing in the low-frequency range, conventional wisdom would suggest that bilateral implantation is the better intervention. Further work is needed in this area to define data-driven guidelines for determining bilateral implant candidacy versus those who would best be served with a bimodal hearing configuration.

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