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The effects of acoustic bandwidth on simulated bimodal benefit in children and adults with normal hearing

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Abstract

Objectives—The primary purpose of this study was to examine the effect of acoustic bandwidth on bimodal benefit for speech recognition in normal-hearing children with a cochlear implant (CI) simulation in one ear and low-pass filtered stimuli in the contralateral ear. The effect of acoustic bandwidth on bimodal benefit in children was compared to the pattern of adults with normal hearing. Our hypothesis was that children would require a wider acoustic bandwidth than adults to 1) derive bimodal benefit, and 2) obtain asymptotic bimodal benefit.

Design—Nineteen children (6–12 years) and ten adults with normal hearing participated in the study. Speech recognition was assessed via recorded sentences presented in a 20-talker babble. The AzBio female-talker sentences were used for the adults and the pediatric AzBio sentences (BabyBio) were used for the children. A CI simulation was presented to the right ear and low-pass filtered stimuli were presented to the left ear with the following cutoff frequencies: 250 Hz, 500 Hz, 750 Hz, 1000, and 1500 Hz.

Results—The primary findings were 1) adults achieved higher performance than children when presented with only low-pass filtered acoustic stimuli, 2) adults and children performed similarly in all the simulated CI and bimodal conditions, 3) children gained significant bimodal benefit with the addition of low-pass filtered speech at 250 Hz, and 4) unlike previous studies completed with adult bimodal patients, adults and children with normal hearing gained additional significant bimodal benefit with cutoff frequencies up to 1500 Hz with most of the additional benefit gained with energy below 750 Hz.

Conclusions—Acoustic bandwidth effects on simulated bimodal benefit were similar in children and adults with normal hearing. Should the current results generalize to children with CIs, these results suggest pediatric CI recipients may derive significant benefit from minimal acoustic hearing (<250 Hz) in the non-implanted ear and increasing benefit with broader bandwidth. Knowledge of the effect of acoustic bandwidth on bimodal benefit in children may help direct clinical decisions regarding a second CI, continued bimodal hearing, and even optimizing acoustic amplification for the non-implanted ear.

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Keywords

bimodal hearing; bimodal benefit; children; cochlear implants; acoustic bandwidth; speech recognition; spectral resolution

Introduction

Cochlear implants (CIs) provide substantial communicative benefit such that average auditory only monosyllabic word recognition in quiet is now in the range of 60 to 70% for adult and pediatric recipients (e.g. Davidson et al. 2010; Gifford, Dorman, et al. 2014; Holden et al. 2013). Limitations to speech recognition for CI recipients are primarily driven by poor spectral resolution and loss of temporal fine structure associated with envelope-based signal processing strategies. Bimodal hearing, therefore, may afford greater spectral resolution and temporal fine structure cues via acoustic hearing in the low- to mid-frequency region of the non-CI ear. In fact, Zhang and colleagues have shown that even when acoustic hearing in the non-CI ear is quite poor, residual frequency selectivity is generally better than that offered by the CI (Dorman, Spahr, Gifford, Cook, Zhang, Loiselle, Whittingham, et al. 2012; Zhang et al. 2013). This holds great promise for CI recipients, as bimodal hearing is more prevalent than ever. Indeed, approximately 60% of modern-day, adult CI recipients have aidable acoustic hearing in the non-implanted ear with audiometric thresholds up to 80–85 dB HL at 250 Hz (Dorman et al. 2010). Some CI recipients also have residual aidable acoustic hearing in the implanted ear preserved through minimally invasive surgical techniques (e.g. Gstoettner et al. 2008). These individuals then have the potential to benefit from bilateral acoustic hearing with their CI. This study, however, only focused on bimodal hearing (i.e. a cochlear implant paired with contralateral acoustic hearing).

Numerous studies have demonstrated bimodal benefit in quiet and in noise for pediatric and adult CI recipients and in vocoder-based simulations with normal-hearing listeners (Brown et al. 2009a, 2009b; Chang et al. 2006; Ching et al. 2006; Dorman et al. 2008; Dunn et al. 2005; Kong et al. 2007; Kong et al. 2005; Mok et al. 2010; Mok et al. 2006; Sterling W. Sheffield et al. 2014; Zhang et al. 2010). Studies have shown that very little acoustic hearing is required in order to derive benefit from bimodal hearing for adult listeners. Specifically, significant bimodal benefit has been observed with low-pass acoustic bandwidths as narrow as 125 to 250 Hz (e.g. Brown et al. 2010; Sheffield et al. 2012; S. W. Sheffield and R. Gifford 2014; Zhang et al. 2010). Further, studies in adults with CIs have shown average bimodal benefit to reach asymptote for both male and female talkers in noise with acoustic low-pass filtered bandwidths of 500 Hz (S. W. Sheffield and R. Gifford 2014; Zhang et al. 2010). Though research has shown that average bimodal benefit does not significantly increase beyond 500 Hz, individual data has revealed considerable variability. Some adults with CIs gain additional benefit with increasing bandwidth above 500 Hz (S. W. Sheffield and R. Gifford 2014), while other listeners experience no benefit or a detriment with increasing bandwidth due to degree of hearing loss or cochlear dead regions above 500 Hz (Zhang et al. 2014).

All previous studies examining the acoustic bandwidth required for bimodal benefit have been conducted with adult listeners. Comparable data for pediatric bimodal listeners could provide diagnostically relevant information to aid clinical decision-making regarding bimodal or bilateral CI candidacy. Indeed, there have been a number of studies reporting that children with normal hearing as well as children with hearing aids both require a broader acoustic bandwidth than hearing-matched adults for rapid word learning and maximum speech understanding (e.g. Pittman et al. 2005; Stelmachowicz et al. 2007; Stelmachowicz et al. 2004). Though these studies have not specifically investigated children with CIs, one could infer that these results may translate to children requiring broader acoustic bandwidth in the non-CI ear to obtain asymptotic bimodal benefit for speech understanding. Identifying optimal hearing conditions is especially crucial for children who are developing speech and language and are more reliant on bottom-up processing cues than adults (e.g. Snedeker et al. 2004).

Similar to the bimodal hearing simulation literature in normal-hearing adults, simulations of bimodal benefit in normal-hearing children can inform hypotheses and expectations in children with CIs. There is limited research in children listening to CI simulations for speech perception. CI simulations (vocoders) are known to reduce spectral resolution similar to CIs (Friesen et al. 2001). There is also some evidence that age affects spectral resolution in young (ages 5–11) children (Allen et al. 1992; Peter et al. 2014). Thus, the effects of vocoder processing on the spectral resolution of young children might vary with age. Additionally, bimodal benefit in adults has been shown to vary with spectral resolution in the acoustic ear (Zhang et al. 2013). Consequently, we examined age effects on the spectral resolution of the children in this study with and without the imposed vocoder (CI simulation).

Thus the purpose of this study was to determine the effect of acoustic bandwidth on simulated bimodal benefit in normal-hearing children and to determine whether the patterns differ from those observed for our control group of normal-hearing adults as well as adult CI recipients as reported previously (S. W. Sheffield and R. Gifford 2014). Based on previous studies examining spectral bandwidth required for optimal acoustic amplification in rapid word learning and speech understanding tasks, our primary hypotheses were that children would require wider acoustic bandwidth than adults to gain 1) significant bimodal benefit, and 2) asymptotic bimodal benefit.

Materials and Methods

Participants

Nineteen children (7 female) with normal hearing were recruited for participation as our experimental group. Pediatric participants ranged in age from 6 to 12 years with a mean of 9.3 years. Prior to testing, hearing was screened at 15 dB HL from 250 through 8000 Hz and tympanometry was completed to rule out middle ear pathology. Speech recognition in noise was also screened in children using the Bamford-Kowal-Bench Sentence in Noise (BKB-SIN) test and all children exhibited age-normative scores (Etymotic Research 2005; Holder et al. in press; Killion et al. 2001).

Ten adults (9 female) with normal hearing were recruited as a control group. The control group was recruited to examine the effect of age (children vs. adults) on acoustic bandwidth effects for bimodal benefit. Previous studies have examined the effects of acoustic bandwidth on bimodal benefit in normal-hearing adults, but not with the same testing paradigm as used with the normal-hearing children evaluated in the current study. The adults ranged in age from 22 to 31 years with a mean of 24.5 years. All adults had normal hearing defined as audiometric thresholds < 20 dB HL for frequencies 250 to 8000 Hz.

Stimuli

Bimodal simulations used of a 15-channel noise vocoder (Litvak et al. 2007) paired with acoustic stimuli delivered to the opposite ear with low-pass filter cutoff frequencies of 250, 500, 750, 1000, and 1500 Hz. The vocoder included 15 logarithmically spaced analysis channels (125–8700 Hz) with filter slopes varied to simulated spread of excitation/channel separation and control performance. Vocoder filter slopes were determined and then fixed for a given participant (i.e. used for all experimental conditions). For more details on the vocoder see Litvak et al. 2007. The low-pass filters for the contralateral ear were finite impulse response filters with varying filter lengths to obtain 90 dB/octave roll-off.

Speech recognition was tested in noise with the same 20-talker babble for both adults and children. The speech stimuli used for testing as well as the signal-to-noise ratios (SNRs), however, were different for children and adults. Specifically, sentence recognition was assessed for pediatric participants with the pediatric AzBio corpus (Spahr et al. 2014), also referred to as the BabyBio sentences, at an individually determined SNR. The BabyBio sentences were used, as they are developmentally appropriate for the age range of children included in the study. The SNR for children was individually determined because performance with the CI simulation varied considerably across children. The SNR was chosen to yield approximately 50% correct in the simulated CI only condition. The mean SNR used for testing was +6.2 dB with a range of +2 to +15 dB. As expected, the required SNR was negatively correlated with listener age ($r = -0.66$, $p < 0.004$).

Sentence recognition for the normal-hearing adults was completed with the AzBio corpus (Spahr et al. 2012) at a +5 dB SNR. AzBio sentences were used because they are more appropriate for adult listeners. Though the AzBio sentences contain both female and male talkers, only female talker performance will be reported given that 1) acoustic bandwidth effects differ for male and female talkers (S. W. Sheffield and R. Gifford 2014) and 2) only a female talker was used with the pediatric participants as the BabyBio sentences are currently only available with a female talker. The female spoken AzBio sentences and the BabyBio sentences were both recorded using an average speech rate (4.4 to 5.1 syllables per second) and both include an average of 7 words per sentence. An SNR of +5 dB was chosen to be consistent with the mean SNR used for the pediatric group. All adult participants performed near 50% correct (range of 33 to 61%) on female spoken AzBio sentences in the CI (vocoded) only condition at +5 dB SNR—also consistent with the mean CI only performance for the pediatric group.

Procedures

Speech and noise were both presented to the acoustic and CI simulation ears using ER-3A insert earphones with the participant seated in a sound-treated booth. The CI simulations were presented at 65 dB SPL to the right ear and the low-pass filtered stimuli at the same level (unfiltered level of 65 dB SPL) to the left ear of all participants to control for language lateralization and better ear effects. The level of the filtered stimuli was not adjusted for two reasons. First, the overall levels of the vocoded stimulus and the 1500 Hz low-pass filtered acoustic stimulus were similar with a difference of less than one decibel. Thus, loudness balancing between the two ears was not completed. Second, if the overall levels were matched across low-pass filtered bandwidths, the levels at individual frequencies would vary across filter bandwidths impeding bimodal benefit contrasts across filters. Participants were tested in seven different CI and low-pass filter conditions: CI only, 1500 Hz acoustic only, CI+250 Hz, CI+500 Hz, CI+750 Hz, CI+1000 Hz, CI+1500 Hz. Only four adults were tested in the 1500 Hz acoustic only condition because it was added to the protocol after the first six adults had completed testing. Two BabyBio or AzBio lists were used for each of these seven conditions for children and adults, respectively. This added up to 40 sentences per child and 20 sentences per adult (female only AzBio sentences), per condition. Participants were instructed to repeat the sentences as best they could and were encouraged to guess. Bimodal benefit was defined in two ways: 1) the percentage-point difference in raw scores between the CI only and bimodal conditions, and 2) the percent possible benefit obtained [e.g. (CI+250 Hz – CI only)/(100 – CI only) × 100] as commonly reported elsewhere (Dorman, Spahr, Gifford, Cook, Zhang, Loiselle, Yost, et al. 2012; Zhang et al. 2013).

Training for the pediatric participants was provided for the CI simulation using the Hearing In Noise Test sentences for children [HINT-C (Nilsson et al. 1996)] in quiet so that we did not need to repeat BabyBio lists during experimentation. Training for the adult participants was completed using the AzBio sentences. Participants repeated sentences and were trained until performance reached a plateau (approximately 10 minutes). No training was provided for the low-pass filtered stimuli though the order of conditions was counterbalanced using a modified Latin square technique[1] across participants to control for experience effects.

The children also completed a spectral modulation detection (SMD) task to examine age effects on spectral resolution. The SMD task was the Quick SMD, or QSMD, developed and validated by Gifford and colleagues (Gifford, Hedley-Williams, et al. 2014). In brief, the QSMD included a three-interval, forced choice procedure based on a modified method of constant stimuli. Spectral modulation was achieved by applying logarithmically spaced, sinusoidal modulation to a broadband carrier with a bandwidth ranging from 125 to 5600 Hz. There were six trials presented for each of five modulation depths (10, 11, 13, 14, and 16 dB) and two modulation frequencies (0.5 and 1.0 cycles/octaves) for a total of 60 trials. Each trial was scored as correct or incorrect and spectral resolution was described as the overall percent correct score for all modulation depths at each frequency in the task (chance

[1]Because the number of possible condition orders was not a multiple of the number of subjects, a perfect Latin square could not be completed in the present study.

= 33%). The listener's task was to indicate which interval was "different" by selecting the interval containing the spectral modulation. The listener responded manually using a touchscreen computer monitor on which three squares were arranged horizontally with numerical labels 1, 2, and 3. As in all forced-choice experiments, the participants were instructed to take a guess if uncertain. No feedback was provided. The QSMD task was completed with unprocessed as well as CI simulated (vocoded) spectrally-modulated stimuli. Vanderbilt University Institutional Review Board approval was granted to complete the research activities associated with this study.

Results

Spectral resolution with QSMD task

QSMD results in the unprocessed and vocoded conditions were collected for 17 and 18 of the 19 pediatric participants, respectively. The results for participant #2 in the unprocessed conditions and participant #3 in both conditions were lost due to computer software errors that were not discovered until after the participants had left the laboratory. Mean scores in the unprocessed condition were 70.0 and 77.8% correct for the 0.5 and 1.0 cycle/oct modulation rates, respectively. Mean scores in the vocoded condition were 49.8 and 37.9% correct for the 0.5 and 1.0 cycle/oct modulation rates, respectively. Paired t-tests revealed that vocoding the stimuli significantly decreased spectral modulation detection for both half and one cycle per octave frequencies ($t = 5.3$, $t = 11.4$; $p < 0.0001$, $p < 0.0001$; respectively). Thus the CI simulations did, in fact, significantly impair spectral resolution.

Age effects on the QSMD task are shown in Figure 1. Only results for the 0.5 cycle/oct modulation rate are shown for the following reasons: 1) the results for the 1.0 cycle/oct rate were the same as 0.5 cycle/oct in the unprocessed condition, and 2) mean results for 1.0 cycle/oct were near chance in the vocoded condition. Pearson correlation analysis revealed a significant effect of age on QSMD in the vocoded condition ($r = 0.53$, $p < 0.0195$) but not for the unprocessed condition ($r = 0.46$, $p < 0.062$). One participant, the youngest (6,3 years), performed below chance levels in both the unprocessed and vocoded conditions. Further examination of individual data revealed that the oldest two participants performed similarly in the unprocessed and vocoder conditions, indicating little effect of vocoding for those two participants. In fact their raw scores (80 and 60%) were well within the range of the other participants' scores but the difference between the two conditions for the two children was less than any other participant (3-percentage points each vs. range of 10- to 56-percentage points). These results indicate that the CI simulation yielded impaired spectral resolution for the children, as expected.

Speech recognition with bimodal simulations—Box plots showing the median and distribution of speech understanding scores, in percent words correct, for each of the seven conditions are shown in Figure 2. Children's mean simulated CI only ($n = 19$) and 1500 Hz acoustic only ($n = 19$) scores were 45.9% and 34.6%, respectively. In contrast, adults' mean simulated CI only ($n = 10$) and 1500 Hz acoustic only ($n = 4$) scores were 52.5% and 56.1%, respectively. There was no difference between groups for the CI only performance ($p > 0.1$); however, the adults performed significantly better than the children in the 1500 Hz acoustic only condition ($p < 0.0001$). This finding is not unexpected given previous reports of children requiring broader bandwidth for rapid word learning and speech understanding (Pittman et al. 2005; Stelmachowicz et al. 2004).

Mean performance increased by 22.9-percentage points from CI only to CI+250 in children (45.9% and 68.9%, respectively) and 19.9-percentage points from CI only to CI+250 in adults (44.3% and 64.2%, respectively). Speech understanding continued to increase in the bimodal condition with low-pass filter cutoff for both the pediatric and adult groups. A two factor mixed model analysis of variance (ANOVA) was completed with adult vs. children as the between groups factor and condition (CI only and 5 bimodal filter cutoffs) as the repeated measures factor. Statistical analysis revealed no effect of group, an effect of listening condition, and no interaction [$F_{(1\ 27)} = 0.01$, $p > 0.965$; $F_{(5\ 135)} = 159.8$, $p < 0.0001$; $F_{(5\ 135)} = 1.90$, $p < 0.098$]. Because no difference in bandwidth effects were present between the groups, only the pediatric data will be further discussed as they are of primary interest in the current study.

Post-hoc comparisons (Bonferroni) provided further evidence of significant bimodal benefit and increasing benefit with acoustic bandwidth for the pediatric listeners. Significant bimodal benefit was observed even with the narrowest acoustic bandwidth, <250 Hz [$t = 7.3$, $p < 0.001$]. The degree of bimodal benefit was 5.9-percentage points greater with a 500 Hz low-pass filter than a 250-Hz filter—a difference that was not statistically significant ($p > 0.05$). Bimodal benefit with the 750-Hz condition was 18.1- and 12.2-percentage points greater than the 250- and 500-Hz conditions, respectively [$t = 8.5, 7.6$; $p < 0.0001$, $p < 0.0001$]. Lastly, bimodal benefit was 6.0- and 3.1-percentage points greater with the 1500-Hz condition as compared to the 750- and 1000-Hz conditions, respectively [$t = 4.2, 3.4$; $p < 0.01$, $p < 0.05$]. Many adults and children approached the ceiling of 100% correct in the CI +750, CI+1000, and CI+1500 Hz conditions. It is possible that the magnitude of performance and bimodal benefit at these widest filter bandwidths would have been larger without ceiling effects. However, bimodal benefit was still significantly greater for the 1500 filter than all other filters. Thus, significant bimodal benefit was noted with just 250 Hz and continued to increase significantly with acoustic bandwidth from 250 to 750 Hz and again from 750 to 1500 Hz.

Aside from the post hoc analyses described above, investigation of individual data revealed that all children obtained greater bimodal benefit in the CI+750 condition than the CI+250 Hz condition (range: 4.4- to 33.8-percentage points). All children also exhibited equivalent or greater bimodal benefit in the CI+750 Hz condition as compared to the CI+500 Hz condition (range: 0.8- to 29.7-percentage points). Analyzing individual data using the critical differences for the BabyBio sentences (Spahr et al. 2014), 10 of the 19 children (52.6%) exhibited significantly greater sentence understanding with CI+750 Hz as compared to CI +250 Hz. The additional increase in bimodal benefit, however, was not as consistent above 750 Hz. Only 3 children exhibited significantly greater sentence understanding with CI +1500 Hz as compared to CI+750 Hz. The other 16 children demonstrated no significant differences in bimodal speech understanding between the CI+1500 Hz and CI+750 Hz conditions (range of −9.1 to 10 percentage points).

Bimodal benefit was also examined as the percent possible benefit obtained with each low-pass filter cutoff. For example, mean CI only performance was 45.9% and mean CI+250 Hz performance was 68.9%. Thus, the mean bimodal benefit, in percent, for the 250-Hz condition would be defined as [(68.9 - 45.9)/(100 - 45.9)] × 100 = 52.2%, as described by others (Zhang et al. 2013). Box plots showing the median and distribution of percent possible bimodal benefit obtained for each filter cutoff are both plotted in Figure 3 for the children and adults. As shown in Figure 3, the results are, again, similar between the two groups. Statistical analysis revealed the same trends for this definition of bimodal benefit as previously noted for raw, percentage-point benefit. There was again, no effect of group between pediatric and adult data and no interaction between group and acoustic bandwidth.

Discussion

As indicated with the QSMD task, the children's spectral resolution decreased with vocoding (i.e. CI simulation), as expected. The results also showed an effect of age on spectral resolution, but only with the stimuli processed through the CI simulation and not with unprocessed stimuli. Thus, the age effect with the CI simulations might not be due to an age effect on spectral resolution, per se, but rather an age effect on *vocoded sound perception*. This conclusion is somewhat supported by the vocoding effects being limited in the oldest two participants. Though the age effect on spectral resolution for vocoded stimuli is consistent with previous literature, it should be interpreted with caution (Allen and Wightman 1992; Peter et al. 2014). The sample size in this study is small, particularly at each age in years. Additionally, we used the QSMD task which was designed for and validated with adult listeners (Gifford, Hedley-Williams, et al. 2014). The children were not trained on this task before testing, which may have influenced the youngest child's chance performance, in particular. Additionally, previous research has shown that these tasks can be affected by cognitive factors such as attention and memory in children in this age range (Jensen et al. 1993). Clearly further research with larger sample sizes is needed in this area to investigate the effect of age between 5 and 12 years for vocoded sound perception and spectral resolution.

Bimodal benefit results suggest that the acoustic bandwidth effects for bimodal benefit are similar in children and adults with normal hearing. Both groups gain significant bimodal benefit with a low-pass filtered acoustic stimulus with a 250-Hz cutoff. Additionally, performance improved similarly in both groups as the low-pass filter cutoff increased from 250 to 750 Hz and again from 750 to 1500 Hz. Thus, these results are contrary to our hypothesis that children would require a wider acoustic bandwidth to obtain both significant and asymptotic bimodal benefit than a control group of normal-hearing adults (S. W. Sheffield et al. 2014).

The current results are also similar to those reported for adult bimodal listeners (S. W. Sheffield and R. Gifford 2014) as the pediatric and adult listeners with normal-hearing also gained significant bimodal benefit for female talker speech recognition in noise with a 250 Hz low-pass filtered stimulus. Contrary to children and adults with normal hearing, however, Sheffield and Gifford (2014) showed that adult CI listeners exhibited no significant increases in bimodal benefit beyond 500 Hz for speech in noise. This difference is most likely due to the sloping hearing losses for the adult CI listeners as reported by Sheffield and Gifford (2014). Specifically, mean audiometric thresholds were approximately 70 dB HL at 750 and 1000 Hz and >90 dB HL for 1500 Hz and above. Further investigation is needed with pediatric CI recipients in a bimodal hearing configuration to investigate whether children require broader acoustic bandwidths to achieve significant and asymptotic bimodal benefit as compared to adults.

This study provides the first look at acoustic bandwidth effects for pediatric bimodal hearing with normal-hearing participants listening to CI simulations. Though these data will provide a solid framework for further investigation with pediatric CI recipients, this study is not without limitations. One limitation of the current study was that the low-pass filtered stimulus delivered to the “non-CI” ear was not spectrally smeared to simulate impaired frequency selectivity associated with sensory-based hearing loss. Thus, the normal-hearing participants in this study likely had better spectral resolution than the typical bimodal listener. This better spectral resolution may have allowed the normal-hearing participants to gain greater bimodal benefit than individuals with sensory hearing loss for broader acoustic bandwidths (e.g. Neuman et al. 2013; S. W. Sheffield and R. Gifford 2014; Zhang et al. 2010). It is also possible that factors of audibility/sensation level and spectral resolution both contributed to the differences in the results from the current study and the results in the literature on adults with CIs. This is especially true given the known effects of high presentation levels on speech understanding (e.g. Rankovic 1991; Studebaker et al. 1999) and the fact that the adult CI recipients have generally derived less benefit from broader acoustic bandwidths than either of the normal-hearing groups in the current study (S. W. Sheffield and R. Gifford 2014; Zhang et al. 2010).

The lack of spectral smearing for acoustic stimuli with bimodal simulations is consistent with other studies examining bimodal hearing for normal-hearing individuals (Brown and Bacon 2009a, 2009b; Chang et al. 2006; Helms Tillery et al. 2012; Kong and Carlyon 2007; Qin et al. 2006). For example, Kong and Carolyn (2007) tested sentence recognition at a +5 dB SNR and found an average of approximately 25-percentage points bimodal benefit. This degree of bimodal benefit is very similar to the average bimodal benefit the current participants gained with a 500 Hz low-pass filter. Thus, the current results are similar to previous studies examining bimodal hearing with both normal-hearing individuals and adults with CIs.

Given the effect of age on the SNR required for approximately 50% performance in the simulated CI only condition for the pediatric participants, we completed post hoc analyses examining age effects on both raw performance and bimodal benefit in children. No correlation was found between age and 1500 Hz acoustic only performance. Significant positive correlations were found, however, between age and raw performance as well as age and percent possible bimodal benefit obtained in the CI+500 Hz condition as shown in Figure 4 ($p < 0.025$, $p < 0.021$, respectively). Interestingly, no significant correlation was found between age and any other bimodal condition for performance or benefit. It is important to note that no correction was made for multiple comparisons for these correlation analyses. We chose not to incorporate corrections in order to maximize the statistical power to detect any effect of age given that no previous data were available to formulate our hypotheses.

The restriction of the significant correlation to the 500 Hz low-pass filter condition might be related to the importance of the 500-Hz region for first formant (F1) discrimination. Previous research has shown better vowel F1 recognition with increasing age between 5 and 11 years (Allen and Wightman 1992; Ohde et al. 1996). Allen and Wightman (1992) suggested that the increases in F1 recognition might be related to increases in spectral resolution in the same age range. We found no significant effect of age, however, on the spectral resolution of the children with unprocessed stimuli in the current study. Nevertheless, the effect of age on performance and benefit with the 500-Hz filter could be due to vowel F1 discrimination and/or improvement for spectral resolution with age. It is also possible that language abilities influenced benefit and performance with the 500-Hz filter. No language measures were included in this study. Thus, language abilities for these children were unknown although parents reported no concerns with language. Additionally, if language influenced bimodal benefit and performance this would have likely influenced all conditions rather than just the 500-Hz filter. Nevertheless, the lack of an age assessment remains a potential limitation of the current study. Further research is needed, however, to better determine the characteristics and cause of this age effect on bimodal benefit in the CI +500 Hz condition.

Perhaps the greatest limitation in this study was the presence of ceiling effects for the bimodal hearing simulations, particularly with higher low-pass filter cutoffs. Ceiling effects may have limited the degree of bimodal benefit the participants could obtain. In an attempt to minimize the ceiling effects we converted all scores to rationalized arcsine units (Studebaker 1985). The conversion, however, made no difference in any of the statistical results reported here. Thus, we reported the percent correct scores for clarity, simplicity, and ease of application to clinical populations.

Despite the potential limitation of ceiling effects, this study provides evidence that the effects of acoustic bandwidth on bimodal benefit are similar in children and adults with normal hearing. As previously noted, these results are contrary to our hypothesis and previous work showing children require wider bandwidth for word learning and speech understanding (Pittman et al. 2005; Stelmachowicz et al. 2007; Stelmachowicz et al. 2004). The effect of acoustic bandwidth on bimodal benefit is currently being examined in pediatric CI recipients to compare bimodal benefit between adult and pediatric CI recipients with bimodal hearing.

Summary

Children listening to CI simulations gained significant bimodal benefit, similar to that seen for adults with a low-pass filter cutoff of 250 Hz in the “non-CI” ear. Additionally, children exhibited significant increases in bimodal benefit with the addition of acoustic hearing up to 1500 Hz—with the majority of the increase occurring below 750 Hz, though the presence of ceiling effects may have limited the magnitude of the observed benefit with higher cutoff frequencies. Pediatric results were similar to a control group of adults with normal hearing.

These results differ from what was seen in adults with bimodal hearing who reach a bimodal asymptote in the 250- to 500-Hz range, possibly due to degree of hearing loss in the non-implanted ear (S. W. Sheffield and R. Gifford 2014; Zhang et al. 2010).

The current data suggest that 1) pediatric CI recipients may benefit from minimal acoustic hearing (250 Hz and below) in the non-implanted ear similar to adults with bimodal hearing, 2) bimodal benefit increases significantly with increasing bandwidth up to at least 1500 Hz, and 3) pediatric CI recipients may not require wider acoustic bandwidths than adults to achieve comparable bimodal benefit. Knowledge of the effect of acoustic bandwidth on bimodal benefit may help direct clinical decisions regarding a second CI, continued bimodal hearing, and even optimizing acoustic amplification for the non-implanted ear. Ongoing work is currently examining this research question with pediatric CI recipients.

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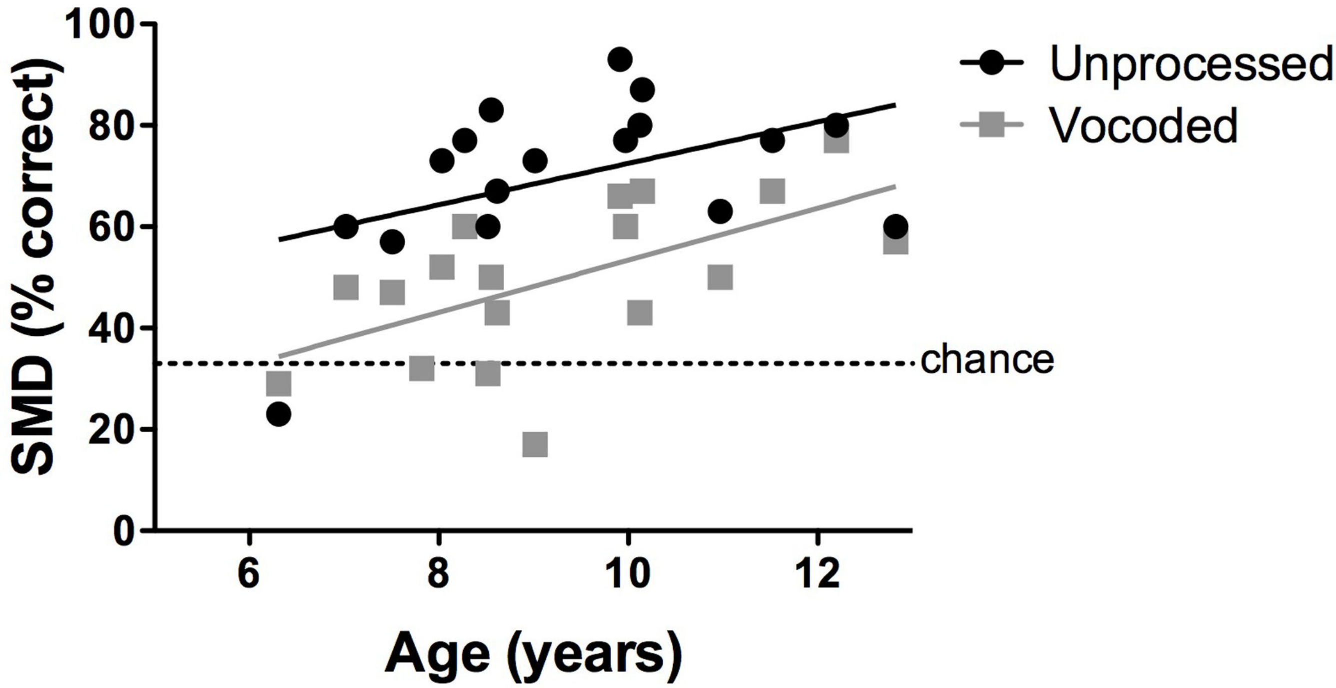

Figure 1.

QSMD scores, in percent correct, for the pediatric participants with the 0.5 cycle/oct modulation rate. Black circles with a black regression line represent unprocessed scores and gray squares with a gray regression line represent vocoded scores. The horizontal dotted line represents chance performance.

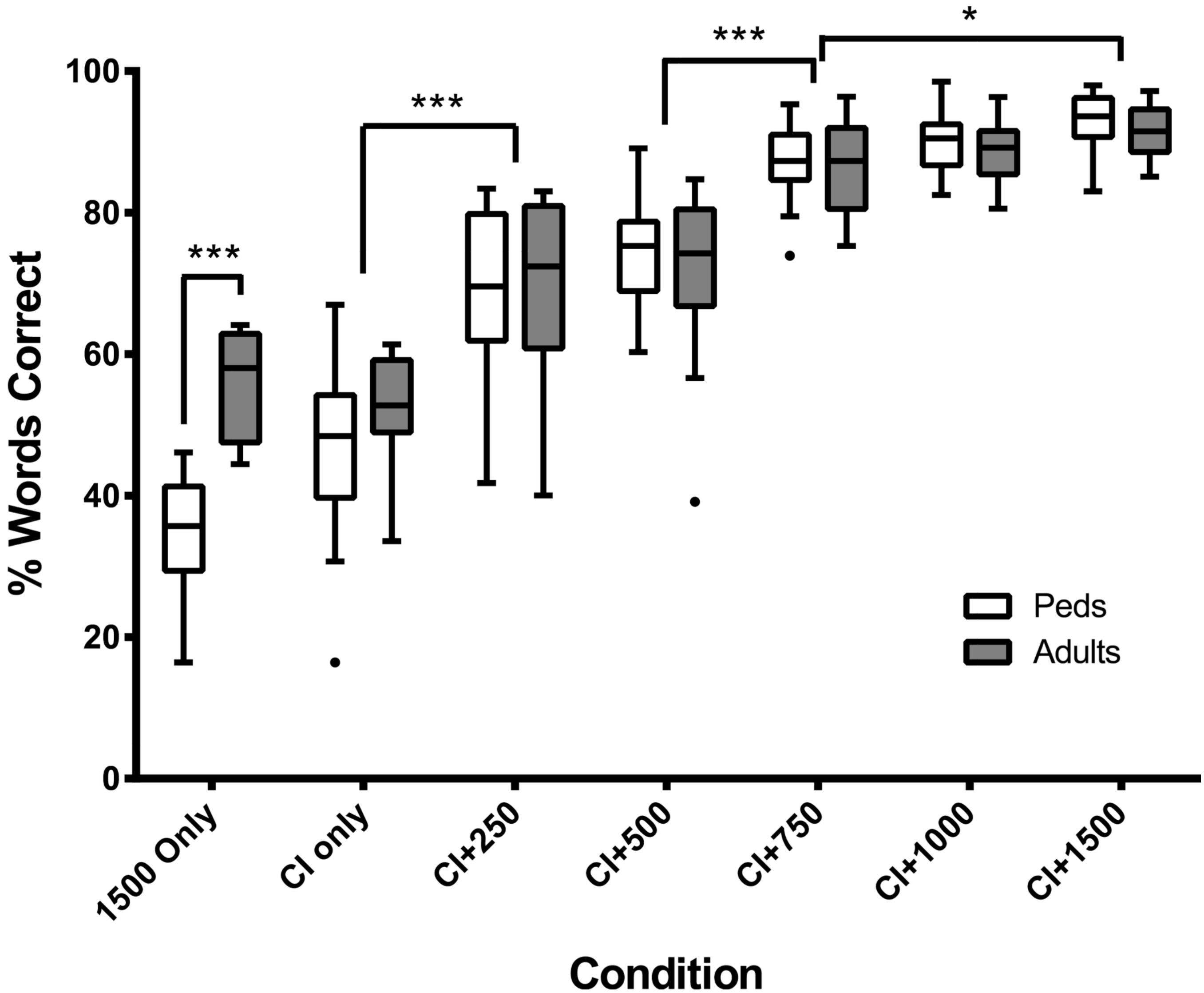

Figure 2.

Speech understanding, in percent words correct, for each of the seven conditions. Box plots show the 25th percentile, the median, and the 75th percentile as the lower, middle, and upper lines of the box, respectively and the whiskers represent the lowest and highest data points within 1.5 interquartile ranges of the lower and upper quartiles. Outliers are plotted as filled black circles. Significant differences, for the pediatric data, are indicated by asterisks, * = $p < 0.05$ and *** = $p < 0.001$. Peds = children. 1500 only = 1500 Hz low-pass filtered speech only in the left ear. CI only = CI simulation only in the right ear. CI+250 = bimodal hearing condition with CI in the right ear and 250 Hz low-pass filtered speech in the left ear. The same pattern is true for CI+500, etc.

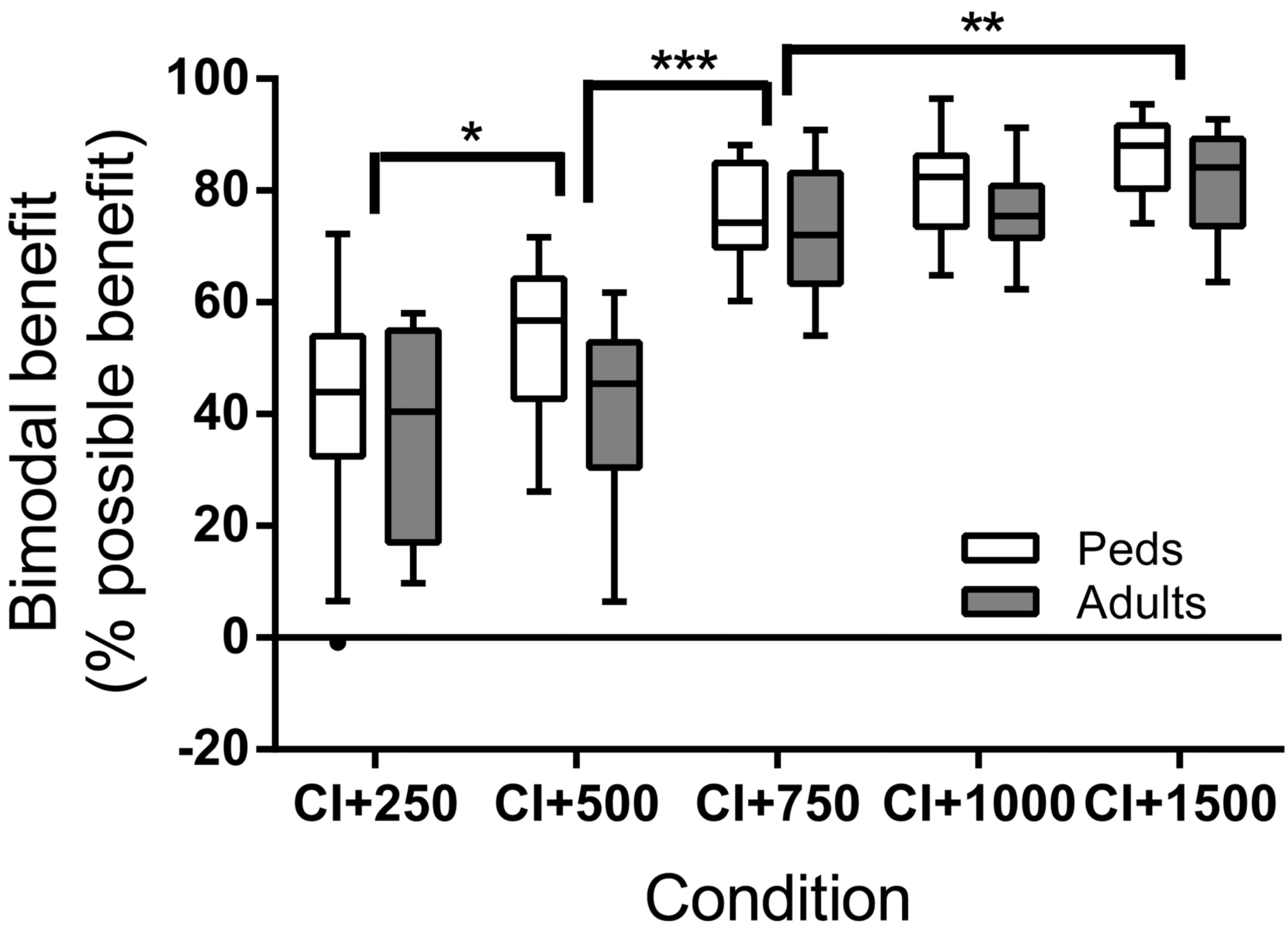

Figure 3.
Percent possible bimodal benefit obtained by children and adults for each low-pass filter conditions. Box plots show the 25th percentile, the median, and the 75th percentile as the lower, middle, and upper lines of the box, respectively and the whiskers represent the lowest and highest data points within 1.5 interquartile ranges of the lower and upper quartiles. Outliers are plotted as filled black circles. Significant differences are indicated by asterisks, * = $p < 0.05$, ** = $p < 0.01$ and *** = $p < 0.001$. Peds = children. CI+250 = bimodal hearing condition with CI in the right ear and 250 Hz low-pass filtered speech in the left ear. The same pattern is true for CI+500, etc.

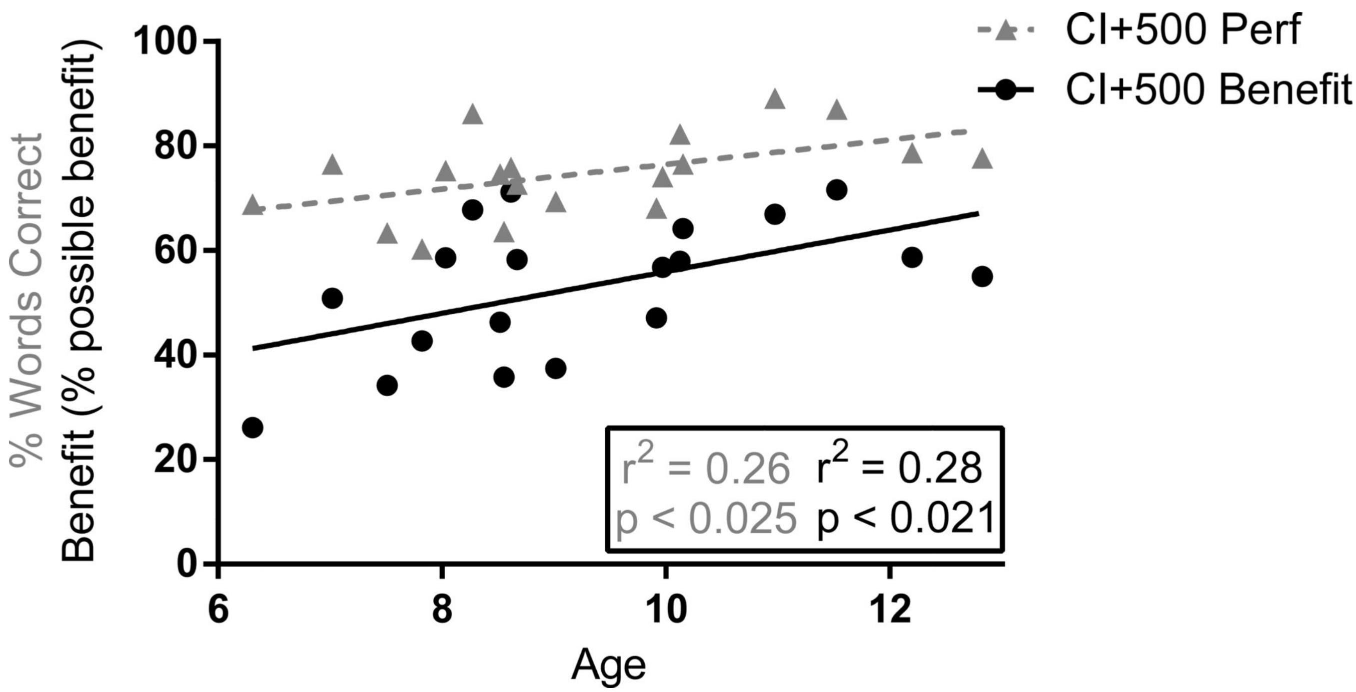

Figure 4.
Raw speech understanding, in percent correct (gray triangles), and bimodal benefit, in percent possible benefit (black circles) for the CI+500 Hz bimodal condition as a function of pediatric participant age, in years. Correlations between speech understanding and participant age as well as bimodal benefit and participant age are displayed in gray and black text, respectively.