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Availability of Binaural Cues for Pediatric Bilateral Cochlear Implant Recipients

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Abstract

Background: Bilateral implant recipients theoretically have access to binaural cues. Research in postlingually deafened adults with cochlear implants (CIs) indicates minimal evidence for true binaural hearing. Congenitally deafened children who experience spatial hearing with bilateral CIs, however, might perceive binaural cues in the CI signal differently. There is limited research examining binaural hearing in children with CIs, and the few published studies are limited by the use of unrealistic speech stimuli and background noise.

Purpose: The purposes of this study were to (1) replicate our previous study of binaural hearing in postlingually deafened adults with AzBio sentences in prelingually deafened children with the pediatric version of the AzBio sentences, and (2) replicate previous studies of binaural hearing in children with CIs using more open-set sentences and more realistic background noise (i.e., multitalker babble).

Research Design: The study was a within-participant, repeated-measures design.

Study Sample: The study sample consisted of 14 children with bilateral CIs with at least 25 mo of listening experience.

Data Collection and Analysis: Speech recognition was assessed using sentences presented in multitalker babble at a fixed signal-to-noise ratio. Test conditions included speech at 0° with noise presented at 0° (S_0N_0), on the side of the first CI (90° or 270°) (S_0N_{1stCI}), and on the side of the second CI (S_0N_{2ndCI}) as well as speech presented at 0° with noise presented semidiffusely from eight speakers at 45° intervals. Estimates of summation, head shadow, squelch, and spatial release from masking were calculated.

Results: Results of test conditions commonly reported in the literature (S_0N_0 , S_0N_{1stCI} , S_0N_{2ndCI}) are consistent with results from previous research in adults and children with bilateral CIs, showing minimal summation and squelch but typical head shadow and spatial release from masking. However, bilateral benefit over the better CI with speech at 0° was much larger with semidiffuse noise.

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Conclusions: Congenitally deafened children with CIs have similar availability of binaural hearing cues to postlingually deafened adults with CIs within the same experimental design. It is possible that the use of realistic listening environments, such as semidiffuse background noise as in *Experiment II*, would reveal greater binaural hearing benefit for bilateral CI recipients. Future research is needed to determine whether (1) availability of binaural cues for children correlates with interaural time and level differences, (2) different listening environments are more sensitive to binaural hearing benefits, and (3) differences exist between pediatric bilateral recipients receiving implants in the same or sequential surgeries.

Keywords

binaural hearing; cochlear implant; children

INTRODUCTION

Bilateral cochlear implant (CI) recipients theoretically have access to binaural cues allowing them to take advantage of head shadow (HS), squelch (also commonly referred to as *binaural unmasking of speech*), spatial release from masking (SRM), and summation. HS is a physical effect in which the head provides an acoustic barrier resulting in level differences between the ears. If one ear is closer to the noise source, the other ear has a higher or better signal-to-noise ratio (SNR). Squelch refers to a binaural effect in which an improvement in the SNR results from a central comparison of time and intensity differences for signals and noise arriving at the two ears. Squelch is typically calculated as the increase in performance with the addition of the ear with a poorer SNR. Summation refers to the effect of having redundant information at the two ears. SRM refers to the improvement in speech recognition obtained as a result of spatially separating speech and noise when listening with both ears. Because *binaural hearing* is not required to derive benefit from HS or SRM, only summation and squelch are effects representative of binaural hearing.

A number of published studies have documented benefits of bilateral cochlear implantation including summation, equivalent HS across ears, the presence of squelch, and SRM (Schleich et al, 2004; Litovsky et al, 2006; Wackym et al, 2007; Buss et al, 2008; Dunn et al, 2008; Zeitler et al, 2008; Eapen et al, 2009; Verhaert et al, 2012). Bilateral cochlear implantation equates to a summation benefit of approximately 10 percentage points for word recognition above that achieved with the better performing ear (Gantz et al, 2002; Müller et al, 2002; Schleich et al, 2004; Litovsky et al, 2006; Buss et al, 2008; Dunn et al, 2008; Zeitler et al, 2008; Gifford et al, 2014). Although reports have documented binaural squelch in bilateral CI recipients, squelch estimates are generally quite small. Squelch has been shown to range from 0.9–1.9 dB improvement in the SNR (Schleich et al, 2004; Litovsky et al, 2006; Nittrouer et al, 2013) and 8.0–18.0 percentage point improvement in fixed SNR listening tasks (Laszig et al, 2004; Buss et al, 2008; Eapen et al, 2009; Verhaert et al, 2012). In a review of bilateral cochlear implantation, van Hoesel (2012) pointed out that estimates of squelch typically include an HS component. He further explains that estimates of squelch for bilateral CI users beyond the contributions of HS are extremely limited (approximately 1 dB).

Such a small magnitude for observed squelch is not unexpected given that (1) interaural time differences (ITDs) are not well transmitted in the envelope-based signal processing strategies used by commercially available CI processors, and (2) CI processors lack temporal synchronization. With respect to the first point, however, ITDs are present in the transmitted envelope and could thus provide the bilateral CI recipient access to binaural cues. A number of studies, however, have shown that envelope ITDs in adults with CIs yield little to no spatial hearing benefit for signals containing interaural level differences (ILDs) (van Hoesel, 2004, 2012).

The studies referenced thus far have all included adult CI recipients with a postlingual onset of deafness for whom the spatial hearing system had developed normally via acoustic hearing earlier in life. Thus, the goal of the implants for these postlingually deafened adults was in the restoration of hearing, which requires the recipient to make use of the available cues for spatial hearing. In other words, the adult bilateral CI recipient must adapt in response to the new, electric stimulation and the altered set of spatial hearing cues. These altered cues include ILDs, which are present yet attenuated as a result of the processor AGC circuits (Grantham et al, 2008), and envelope-based ITDs (as opposed to fine-structure ITDs).

Few published studies have evaluated binaural cues available to pediatric bilateral CI recipients. Van Deun et al (2010) examined binaural hearing effects for a group of normal-hearing adults and children as well as for eight children with bilateral CIs. With use of an adaptive number identification task with a speech-weighted, steady-state noise, the children with bilateral implants demonstrated HS effects and SRM similar to that of their normal-hearing peers, but no evidence of either summation or squelch. Their conclusions, however, may have been clouded by considerable intersubject variability, which was particularly problematic given the small sample size.

Murphy et al (2011) examined SRM in a group of normal-hearing children and children with bilateral CIs. They tested speech recognition using an adaptive speech reception threshold task with a closed set of spondee words in a background of steady-state pink noise. SRM was significant and similar in both groups, although absolute thresholds were better for the normal-hearing group.

Nittrouer et al (2013) examined summation and SRM in children with bilateral CIs. The children demonstrated significant summation for word recognition in quiet and in noise. Summation for word recognition in quiet was approximately 10 percentage points and was thus consistent with adult outcomes. Summation for word recognition in noise was small (3.0–4.0 percentage points) yet significant. SRM was present for the bilateral CI recipients, though not significantly different from that exhibited by children—with just one CI—again demonstrating that binaural hearing is not a prerequisite for SRM.

Lastly, Chadha et al (2011) measured binaural summation and SRM in children with bilateral CIs that were either sequentially or simultaneously implanted in each ear. They used an adaptive speech detection paradigm with a monitored live-voice stimulus /baba/ spoken by a male voice and a speech-shaped background noise. They reported significant

SRM in both groups, but children with simultaneous implantation had SRM values similar to those in a normal-hearing control group, whereas children with sequential implantation had significantly lower SRM values. Similarly, Chadha and colleagues found significant binaural summation in children with simultaneous implantation but not in children with sequential implantation.

The results of these pediatric bilateral CI studies are very similar to those in adults with bilateral CIs showing present HS and SRM but minimal binaural effects (i.e., summation and squelch). However, the stimuli and background noise used for testing children in the studies were different from those typically used for adults. The stimuli used for the pediatric studies included closed-set and single words rather than sentences. Furthermore, the background noises were steady state rather than multitalker babble often used with adults as well as typically encountered in real-world listening environments. These details are of importance because (1) the target stimuli for adults and children in typical communicative environments are sentences with contextual information; and (2) the background noise in most communicative environments includes speech, not steady-state noise. It is possible that the use of closed-set stimuli and single words in a steady-state background may not have sufficiently taxed the auditory system in such a way as to highlight the potential benefits afforded by the presence of binaural cues. Additionally, research in adults indicates slightly more HS and summation and less squelch in studies using steady-state noise (Laszig et al, 2004; Schleich et al, 2004) than those using multitalker babble (Litovsky et al, 2009; Gifford et al, 2014). Thus, these differences may in fact preclude direct comparison across the adult and pediatric outcomes for the published dataset so far.

Children with congenital hearing loss who receive implants early in life may further represent an entirely different model of spatial hearing development. The neural system must interpret and combine the altered and disparate spatial cues provided by the implants in order to map a central representation of auditory space. Given that the auditory system is developing via CI stimulation, it is possible that the envelope ITD cues present in current envelope-based signal processing strategies and the attenuated ILD cues present with the processor AGC circuits may combine to provide a different central representation of binaural hearing than for the postlingually deafened adult. In other words, children may demonstrate different benefit from bilateral cochlear implantation.

The purposes of this study were to (a) replicate our previous study of binaural hearing in postlingually deafened adults in prelingually deafened children (Gifford et al, 2014), and (b) replicate previous studies of binaural hearing in children with CIs with more real-world stimuli and background noise. The current null hypotheses were that (a) prelingually deafened pediatric bilateral CI recipients would exhibit the same binaural hearing (i.e., estimates of summation and squelch) as postlingually deafened adult bilateral CI recipients (e.g., Gifford et al, 2014), using the same experimental design with the pediatric version of the AzBio sentences (Spahr et al, 2012, 2014) in the presence of multitalker babble; and (b) binaural hearing cue estimates in children with CIs would be the same with more real-world stimuli as those in the literature with closed-set stimuli and steady-state noise.

MATERIALS AND METHODS

This study was divided into two experiments, and the Materials and Methods and Results sections were divided accordingly.

Participants

Experiment I—Demographic information for the 14 pediatric bilateral CI participants is shown in Table 1. Variables provided include age at testing, gender, age at implantation, experience with implants, first CI ear, implant manufacturer, and CI processor. All participants were congenitally deafened with severe-to-profound sensory hearing loss before implantation. Thus, the length of deafness for each participant and each ear is equivalent to the age of implantation. Participants' ages ranged from 6.3–14.1 yr (mean age = 9.8 yr). Participants received their first implant at an average age of 2.8 yr (age range = 0.9–7.3 yr) and the second implant (for the sequential recipients) at an average age of 5.5 yr (age range = 1.8–9.9 yr). Participants had an average of 7.0 yr of experience (range = 2.0–12.4 yr) with the first implant. All but one participant received the implants in sequential surgeries. For the 13 participants receiving their implants in sequential surgeries, the average experience with the second implant was 4.4 yr (range = 0.9–7.7 yr) with a mean difference in experience between the two implants of 2.7 yr (range = 0.4–7.2 yr). For the 13 sequential recipients, in all but two participants (P3, P10), the first CI ear yielded equivalent or significantly better performance than the second CI ear as indicated by a binomial distribution model for the BabyBio sentences (Spahr et al, 2014) presented in noise at S_0N_0 . The two participants (P3, P10) for whom the second CI ear yielded significantly better performance than the first CI ear are indicated by an asterisk in the column labeled *1st CI ear*. All participants used hearing aids in both ears before implantation.

Experiment II—Eight of the original 14 participants (P5, P6, P7, P8, P9, P12, P13, and P14) were willing and able to return for participation in *Experiment II*. No additional inclusion criteria were included for this experiment. See Table 1 for demographic details.

Methods

Experiment I—The methods of this experiment were very similar to those of a previous study in our laboratory with adults with bilateral CIs (Gifford et al, 2014). Speech recognition was assessed using the pediatric version of the AzBio sentences, nicknamed the “BabyBio” sentences (Spahr et al, 2014), presented with spatially separated multitalker babble in three different noise conditions. The noise signal was presented from either the front (S_0N_0), from the side of the first CI (90° or 270° azimuth: S_0N_{1stCI}), or from the side of the second CI (90° or 270° azimuth: S_0N_{2ndCI}). The BabyBio sentences were presented at 65 dBA and always at 0° azimuth. The level of the multitalker babble was individually determined so as to place speech perception performance in the range of 40–60 percent correct in the better CI condition for S_0N_0 . This manipulation was chosen to avoid both ceiling and floor effect confounds. The SNRs required ranged from 0.0 to 115.0 dB, with an average of 5.8 dB. Sentence recognition was assessed for all noise conditions for each ear individually as well as the bilateral CI condition. Participants used their everyday CI programs and were not permitted to manipulate settings during testing.

Binaural summation, HS, SRM, and squelch were calculated for each participant. The calculations are described in detail in the Results section. The binaural hearing estimates for HS, SRM, and squelch were calculated for the first and second as well as the better and poorer implanted ears to evaluate effects of duration of deafness and performance, respectively. As mentioned previously, only two participants (P3, P10) performed significantly better with the second CI rather than with the first CI. Therefore, the better and poorer ears were equivalent to the first and second ears for most participants. Because of the relatively small sample size and differences in results for the two comparisons, both analyses were completed to determine if the comparisons yielded different results.

Experiment II—Testing was performed using the Revitronix R-SPACE sound simulation system. The R-SPACE system consists of an 8-speaker array with each speaker arranged at 45° intervals in a circle surrounding the listener. Each speaker is 24 inches from the center of the participant's head and simulates a realistic restaurant setting, as described in detail in previous studies (e.g., Compton-Conley et al, 2004; Revit et al, 2007). The purpose of *Experiment II* was to examine binaural benefit or the difference in performance between the better CI and bilateral CI conditions in a realistic restaurant background noise to determine if greater binaural benefit is obtained in a more realistic listening environment with semidiffuse noise.

In *Experiment II*, speech recognition was assessed using the Hearing-In-Noise Test sentences for children, HINT-C (Gelnett et al, 1995), presented from the front (0°). The R-SPACE proprietary restaurant noise was presented from all the speakers in all conditions. The HINT-C sentences were presented at 65 dBA. The level of the noise was individually determined so as to place sentence recognition in the range of 40.0–60.0 percent correct for the better ear condition with speech at 0° azimuth. This manipulation was chosen to avoid ceiling and floor effect confounds. The SNRs required ranged from –3.0 to 14.0 dB with an average of –2.5 dB. Sentence recognition was assessed for all speech conditions for the better ear and the bilateral CI condition. Participants used their everyday CI programs and were not permitted to manipulate settings during testing.

RESULTS

Experiment I

Speech in Quiet and Noise: S_0N_0 —Table 2 contains the scores for the quiet and S_0N_0 listening conditions. Mean performance (in percent correct) for the first implant, second implant, and bilateral conditions in quiet was 85.0, 72.5, and 87.2, respectively. Mean performance (in percent correct) for the first implant, second implant, and bilateral conditions in noise was 46.4, 34.0, and 56.7, respectively. Kolmogorov-Smirnov tests revealed that the data for both quiet and S_0N_0 conditions were not normally distributed (specifically, the quiet sample was not normally distributed). Therefore, nonparametric Friedman and Wilcoxon signed-rank tests were used for analyses.

A single-factor Friedman test of the performance in quiet revealed a significant main effect of listening condition [$\chi^2(2,12) = 11.23, p < 0.004$]. Holm-Sidak post hoc analysis using Wilcoxon signed-rank tests showed that both the bilateral and first implant performances

were greater than the second implant ($p < 0.001$ and $p < 0.007$, respectively). No significant difference was found between the bilateral performance and the first implant performance ($p < 0.116$). The same pattern of results was present when the better and poorer implant performances were compared with the bilateral performance.

A single-factor Friedman test of the speech-in-noise performance in the S_0N_0 condition revealed a significant main effect of listening condition (first CI, second CI, bilateral) [$\chi^2(2,12) = 12.26$, $p < 0.002$]. Holm-Sidak post hoc analysis using Wilcoxon signed-rank tests revealed bilateral performance greater than both the first and second implants ($p < 0.005$ and $p < 0.002$, respectively), but no difference between the performances with each implant individually ($p < 0.124$). However, the pattern of results was different when the better and poorer implants, rather than the first and second, were examined. A single-factor Friedman test of the performance in the S_0N_0 condition revealed a significant main effect of listening condition (better CI, poorer CI, bilateral) [$\chi^2(2,12) = 23.16$, $p < 0.001$]. Holm-Sidak post hoc analysis using Wilcoxon signed-rank tests revealed bilateral and better implant performances greater than the poorer implant performance ($p < 0.001$ for both comparisons), and bilateral performance was significantly greater than better implant performance ($p < 0.016$).

Summation—Estimates of summation were calculated as the difference score between the better implant and the bilateral condition. Summation values are shown in Figure 1. Mean summation was 1.8 and 6.9 percentage points in quiet and S_0N_0 conditions, respectively. Individual estimates of summation ranged from -4.1 to 8 percentage points in quiet and -5.0 to 51.7 percentage points in S_0N_0 .

The difference between the better implant and the bilateral condition (i.e., summation) was not significantly different from zero in quiet but was in the S_0N_0 condition ($p < 0.016$). A Grubb's test revealed the presence of an outlier (51.7 percentage points, $p < 0.05$) in the S_0N_0 condition; however, summation was still significant in this condition when the outlier was removed from the analysis ($p < 0.05$). A Wilcoxon signed-rank test revealed no significant difference between binaural summation values in quiet and S_0N_0 ($p < 0.187$).

Speech in Noise: Spatially Separated Listening Conditions—Table 2 contains individual and mean scores for the spatially separated listening conditions (S_0N_{1stCI} and S_0N_{2ndCI}) for each ear individually, as well as the bilateral condition. As expected, results indicate better performance in either (1) the bilateral condition, or (2) conditions in which noise was presented to the opposite side of the ear being tested (i.e., HS). With the data shown in Table 2, we calculated estimates of HS, SRM, and squelch.

HS—Estimates of HS were calculated as follows:

$$\text{HS for 1}^{\text{st}} \text{ CI} = \text{score for 1}^{\text{st}} \text{ CI}(S_0N_{2ndCI}) - \text{score for 1}^{\text{st}} \text{ CI}(S_0N_{1stCI})$$

$$\text{HS for 2}^{\text{nd}} \text{ CI} = \text{score for 2}^{\text{nd}} \text{ CI}(S_0N_{1stCI}) - \text{score for 2}^{\text{nd}} \text{ CI}(S_0N_{2ndCI})$$

$$\text{HS for better CI} = \text{score for better CI}(\text{noise to poorer CI}) - \text{score for better CI}(\text{noise to better CI})$$

$$\text{HS for poorer CI} = \text{score for poorer CI}(\text{noise to better CI}) - \text{score for poorer CI}(\text{noise to poorer CI})$$

Individual and mean estimates of HS for the first and second implants as well as the better and poorer implants are shown in Figure 2. Mean HS was 23.2, 28.7, 30.7, and 21.1 percentage points for the first, second, better, and poorer implanted ears, respectively. Kolmogorov-Smirnov tests could not reject the null hypothesis that all HS data were normally distributed. Therefore, we completed parametric data analysis with paired *t*-tests of the first and second implants and the better and poorer implants. Statistical analysis revealed no significant differences in HS between the implanted ears ($p > 0.10$ for both).

SRM—Estimates of SRM were calculated as follows:

$$\text{SRM for 1}^{\text{st}} \text{ CI} = \text{score for 1}^{\text{st}} \text{ CI}(S_0N_{2ndCI}) - \text{score for 1}^{\text{st}} \text{ CI}(S_0N_0)$$

$$\text{SRM for 2}^{\text{nd}} \text{ CI} = \text{score for 2}^{\text{nd}} \text{ CI}(S_0N_{1stCI}) - \text{score for 2}^{\text{nd}} \text{ CI}(S_0N_0)$$

$$\text{SRM for better CI} = \text{score for better CI}(\text{noise to poorer CI}) - \text{score for better CI}(S_0N_0)$$

$$\text{SRM for poorer CI} = \text{score for poorer CI}(\text{noise to better CI}) - \text{score for poorer CI}(S_0N_0)$$

$$\text{SRM for bilateral} = \text{score for bilateral}(\text{noise to poorer ear}) - \text{score for bilateral}(S_0N_0)$$

Individual and mean estimates of SRM for the first, second, better, and poorer implanted ears as well as the bilateral condition are shown in Figure 3. Mean SRM was 9.8, 12.1, and 19.3 percentage points for the first and second implanted ears and bilateral condition, respectively. Mean SRM was 14.0 and 7.8 percentage points for the better and poorer implanted ears, respectively. Kolmogorov-Smirnov tests could not reject the null hypothesis that all SRM data were normally distributed; thus, parametric analysis was completed using an analysis of variance (ANOVA). A one-way repeated-measures ANOVA with Greenhouse-Geisser adjustment completed for SRM observed revealed a near-significant effect of listening condition (first CI, second CI, bilateral) [$F(2,12) = 3.26$, $p < 0.068$]. However, the effect of listening condition was significant when better and poorer CI ears were examined. A oneway ANOVA with Greenhouse-Geisser adjustment completed for SRM observed revealed a significant effect of listening condition (better CI, poorer CI, bilateral) [$F(2,12) = 4.8$, $p < 0.027$]. Post hoc analysis using paired *t*-tests with Holm-Sidak corrections revealed

that SRM was significantly greater in the bilateral condition than the poorer CI condition [$t_{(13)} = 2.51, p = 0.026$]. No other comparisons were significant.

Squelch—Estimates of squelch were calculated as follows:

$$\text{Squelch for 1}^{\text{st}} \text{ CI} = \text{score for bilateral CI}(S_0N_{2\text{ndCI}}) - \text{score for 1}^{\text{st}} \text{ CI}(S_0N_{2\text{ndCI}})$$

$$\text{Squelch for 2}^{\text{nd}} \text{ CI} = \text{score for bilateral CI}(S_0N_{1\text{stCI}}) - \text{score for 2}^{\text{nd}} \text{ CI}(S_0N_{1\text{stCI}})$$

$$\text{Squelch for better CI} = \text{score for bilateral CI}(\text{noise to poorer CI}) - \text{score for better CI}(\text{noise to poorer CI})$$

$$\text{Squelch for poorer CI} = \text{score for bilateral CI}(\text{noise to better CI}) - \text{score for poorer CI}(\text{noise to better CI})$$

Individual and mean estimates of squelch for each ear are shown in Figure 4. Mean squelch estimates were 0.39, 14.44, 1.10, and 12.95 percentage points for the first, second, better, and poorer implanted ears, respectively. Kolmogorov-Smirnov tests could not reject the null hypothesis that all SRM data were normally distributed. Because of the detection of an outlier in the data (75.2 via Grubb's test, $p < 0.05$), squelch results were analyzed using nonparametric tests. Paired t -tests revealed the same results as the Wilcoxon signed-rank tests. Wilcoxon signed-rank tests revealed greater squelch in the second CI than in the first CI, but there was no significant difference between better and poorer implanted ears [$\chi^2_{(13)} = 1.98, p < 0.048$; $p < 0.044$ and $\chi^2_{(13)} = 1.29, p < 0.198$, respectively]. Squelch was significantly greater than zero for the second implanted ear [$\chi^2 = 2.04, p < 0.041$] and near significant for the poorer implanted ear ($p < 0.077$) but not for the first or better-implanted ears ($p > 0.78$ for both). Squelch for a poorer ear, however, can be exaggerated with hearing asymmetry (Schafer et al, 2011). Three participants (P9, P12, P13) had a performance asymmetry greater than 30 percentage points between ears. When the data for these three participants were removed, squelch for the second and poorer CI was no longer significant ($p > 0.278$ and $p > 0.44$, respectively).

Experiment II

Figure 5 shows the individual and mean scores for the better CI and bilateral conditions in semidiffuse noise, with speech presented from a speaker at 0° azimuth. The symbol shapes are participant specific and consistent across conditions and azimuths, and the horizontal line represents the mean performance for each condition. The *best CI ear was the right ear for all eight participants* in this experiment. Statistical analyses were not completed for this experiment because of the small sample size.

Mean performance for the best CI and bilateral CI conditions was 63.3 and 81.8% correct, respectively. Thus, mean performance in the bilateral condition was 18.5 percentage points higher than the best CI alone. Seven of eight participants performed better in the bilateral CI

condition compared with the best CI alone, with a bilateral benefit ranging from 12.0–32.7 percentage points (mean = 22.0 percentage points). One participant (P13) performed approximately 5 percentage points poorer with bilateral CIs compared with the best CI alone, possibly because of her poor performance with her second CI.

There is no way to calculate traditional summation, HS, SRM, or squelch in this experiment. However, the difference between the bilateral and better CI conditions with speech presented from 0° in semidiffuse noise is of important consideration. Although speech was presented from the front, the comparison of the two conditions is not solely summation because the noise signal at each ear is different (i.e., noise reaching the ears at various time delays). The comparison of best CI versus bilateral CI with speech at 0° is also not *solely squelch*, as there is no ear with a poorer SNR. The mean increase of 18.5 percentage points with the addition of the poorer ear could be an indication of global binaural hearing. Binaural hearing estimation in this manner was larger than the summation and squelch for the better ear estimations in *Experiment I* (7.0 and 6.9 percentage points, respectively).

DISCUSSION

Experiment I supports significant HS and SRM in children with bilateral CIs, even with sequential bilateral implantation. However, as previously noted, HS and SRM do not require integration of ITD or ILD cues, nor binaural integration. The results of *Experiment I* showed little-to-no summation or squelch for these children with bilateral implants. The results of *Experiment I* were largely consistent with those reported in the literature examining the availability of binaural cues for adults with bilateral implants, including our previous study in adults using a similar design (Gifford et al, 2014). Some estimates were slightly lower than that for adults in the literature, which is consistent with the previous literature examining children with bilateral CIs (Van Deun et al, 2010; Chadha et al, 2011; Murphy et al, 2011).

Mean estimates of HS were consistent with previous reports in the literature ranging from 21.1–30.7 percentage points (Buss et al, 2008; Eapen et al, 2009; Gifford et al, 2014). Summation was slightly lower than that reported in the previous literature in adults in the current study (7.0 percentage points) (e.g., Buss et al, 2008; Eapen et al, 2009).

Mean estimates of squelch were also consistent, ranging from 0.0–14.4 percentage points (Buss et al, 2008; Eapen et al, 2009; Gifford et al, 2014). Squelch was greater in the second implanted or poorer implanted ear, consistent with results in adults (Gifford et al, 2014). This ear effect is likely the result of the difference in overall performance between the ears. Specifically, when adding the ear with a poorer SNR to calculate squelch, a bigger benefit or squelch effect will be measured when adding a better-performing ear. Consistent with this, the participants with the greatest squelch in the second ear had the most asymmetrical performance between ears, with the first ear being the better ear. When these three participants were removed, the difference in squelch between ears and the squelch in the second ear was no longer significant ($p > 0.30$ for both).

Thus, the current study found no evidence to support our hypothesis that pediatric bilateral CI recipients who have acquired speech and language through their implants would demonstrate different benefit from binaural cues than adult bilateral CI recipients. The thought behind this hypothesis was that prelingually deafened children with bilateral CIs might demonstrate different binaural hearing benefit, as they might be better able to extract the envelope-based ITD cues present in the electrical stimulus (i.e., pulse train), given that their auditory system developed in response to electrical stimulation. These results would suggest, however, that like adult bilateral recipients, pediatric bilateral CI recipients are also not able to take advantage of envelope-based ITDs (van Hoesel, 2004, 2012).

Experiment I results were also consistent with those of previous research in children with bilateral CIs using different stimuli and background noise showing minimal evidence of binaural cue integration summation and squelch (Van Deun et al, 2010; Chadha et al, 2011; Murphy et al, 2011). Thus, the use of sentence stimuli and multitalker babble rather than steady-state noise made no difference in estimates of binaural hearing for children with CIs.

It is possible that larger binaural effects in both children and adults could be observed in a different listening environment. *Experiment I* used the classic experimental design to calculate estimates of binaural hearing (Festen and Plomp, 1986). *Experiment II* was included for a subgroup of eight participants to further examine the availability of binaural cues in a realistic restaurant background noise.

Experiment II examined differences in performance between the best CI and bilateral CI condition, with speech presented from the front and restaurant noise presented in a semidiffuse manner all around the participant (S_0N_{0-360}). This environment is more realistic because background noise rarely has a single source azimuth, such as S_0N_0 , and speech and noise generally do not originate from the same source. Thus, testing in this restaurant noise environment might be a better representation of the improvement that individuals with CIs gain from binaural hearing in their daily lives.

Experiment II showed some evidence of greater binaural hearing cue integration to improve speech recognition than *Experiment I*. Mean bilateral performance was nearly 20 percentage points higher than the better CI performance with speech presented from the front. The benefit of bilateral hearing versus the better CI with speech from the front is not strictly any of the four estimates of binaural effects we have described. Because this condition did not include a CI with poorer SNR, we cannot directly calculate squelch. Furthermore, because noise reaches the ears at various time delays, we cannot calculate a pure estimate of summation. Rather, the improvement with two CIs as measured in this S_0N_{0-360} condition might best be described as what Van Deun and colleagues have called *bilateral unmasking* (often used interchangeably with squelch). Binaural unmasking involves a noise reduction resulting from comparisons of the interaural characteristics of speech and noise (Van Deun et al, 2010). Regardless of the label provided, this bilateral benefit over the better CI seems to provide evidence of binaural hearing benefit or integration of the separate speech-and-noise signals.

Further research is needed in this area for many reasons. First, future work should focus on correlations with ITD and ILD data, to determine whether this *bilateral benefit* is related to binaural hearing mechanisms. Second, future work should also examine whether demographic characteristics are associated with binaural hearing benefit across children. One example is whether children receiving their bilateral CIs in a single surgery have different binaural hearing benefit than those receiving them in sequential surgeries, which may have been separated by several years. It is possible that young children with simultaneous bilateral CI placement may be in a better position to take advantage of the envelope-based ITD cues existing in the electrical pulse trains across ears. That is, simultaneous bilateral recipients receiving their implants at a very young age may be better able to extract the spatial cues provided by the implants to provide a better central representation of binaural hearing than for either the postlingually deafened adult or the child with a sequential implant. However, as noted, further research is needed with a much larger sample size to determine any possible benefits of simultaneous implantation and effects of demographic characteristics.

CONCLUSIONS

The purposes of the current study were to replicate our previous study of binaural hearing in postlingually deafened adults in prelingually deafened children (Gifford et al, 2014) and to replicate examination of binaural hearing in pediatric bilateral CI patients using more real-world stimuli and background noise. Results using testing methods common in the literature (S_0N_0 , S_0N_{90} , S_0N_{270}) revealed similar summation, HS, SRM, and squelch to results reported in the literature for both adult bilateral CI recipients with the similar stimuli and noise and pediatric bilateral recipients with closed-set stimuli and steady-state noise. In short, HS and SRM are significant and similar to children with normal hearing per previous reports in the literature, and summation and squelch are minimal.

A second experiment examining availability of binaural cues in semidiffuse noise and speech presented from 0°, however, showed greater binaural benefit. Thus, it is possible that testing in different environments might reveal more binaural hearing benefit for all CI patients across the age span. Further research is needed in different acoustic environments such as semidiffuse background noise. Further research is also needed to determine the binaural hearing benefits of simultaneous rather than sequential implantation and the correlation of ITDs and ILDs to binaural cues in children with bilateral CIs.

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Abbreviations:

CI cochlear implant

HINT-C	Hearing-In-Noise Test sentences for children
HS	head shadow
ILD	interaural level difference
IQR	interquartile ratio
ITD	interaural time difference
SNR	signal-to-noise ratio
SRM	spatial release from masking
S₀N₀	speech and noise at 0°
S₀N_{1stCI}	speech at 0° and noise at 90° or 270° for right or left CIs, respectively
S₀N_{2ndCI}	speech at 0° and noise at 90° or 270° for right or left CIs, respectively
S₀N₀–360	speech at 0° and semidiffuse noise

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Figure 1.

Box-and-whisker plots for summation in the quiet and S_0N_0 listening conditions.

Summation = bilateral CI – better CI performance. The plus signs (+) represent the means, the center lines the medians, and the upper and lower lines the 75th and 25th percentiles.

The whiskers are plotted according to Tukey's method at the most extreme value within 1.5 interquartile ratio (IQR) of the 25th and 75th percentiles. Filled circles represent outliers.

Summation was significantly greater than zero in the S_0N_0 condition, but not in quiet. No significant difference was found between summation in quiet and summation in S_0N_0 . A significant difference from zero is indicated with an asterisk ($p < 0.05$). Summation was significantly greater than zero in the S_0N_0 condition, but not in quiet. No significant difference was found between summation in quiet and summation in S_0N_0 .

Figure 2.

Box-and-whisker plots for HS for both the first and second CIs as well as better and poorer CIs [e.g., HS for first CI = first CI ($S_{0N_{2ndCI}}$) – first CI ($S_{0N_{1stCI}}$)]. The horizontal line at 0 percentage points represents no HS. The plus signs (+) represent the means, the center lines the medians, and the upper and lower lines the 75th and 25th percentiles. The whiskers are plotted according to Tukey's method at the most extreme value within 1.5 IQR of the 25th and 75th percentiles. All HS estimates were significantly greater than zero (indicated by asterisks), but no difference was found between the first and second ears or better and poorer ears.

Figure 3.

Box-and-whisker plots for SRM for the first, second CIs, better, and poorer CIs as well as the bilateral condition [e.g., SRM for first CI 5 score for first CI ($S_{0N_{2ndCI}}$) – score for first CI (S_{0N_0})]. The horizontal line at 0 percentage points represents no SRM. The plus signs (+) represent the means, the center lines the medians, and the upper and lower lines the 75th and 25th percentiles. The whiskers are plotted according to Tukey's method at the most extreme value within 1.5 IQR of the 25th and 75th percentiles. Filled circles represent outliers. All SRM estimates were significantly greater than zero (indicated by asterisks over box plots). The only difference found between conditions was greater SRM in the bilateral condition than in the poorer ear condition (indicated by a bracket between conditions with an asterisk).

Figure 4.

Box-and-whisker plots for binaural squelch for the first and second CI as well as the better and poorer [e.g., Squelch for first CI = score for bilateral CI ($S_{0N_{2ndCI}}$) – score for first CI ($S_{0N_{2ndCI}}$)]. The horizontal line at 0 percentage points represents no squelch. The plus signs (+) represent the means, the center lines the medians, and the upper and lower lines the 75th and 25th percentiles. The whiskers are plotted according to Tukey's method at the most extreme value within 1.5 IQR of the 25th and 75th percentiles. Filled circles represent outliers. Squelch was only significantly greater than zero for the second CI. Additionally, squelch for the second CI was significantly greater than squelch for the first CI. A significant difference between conditions is indicated with brackets and an asterisk, and a significant difference from zero is indicated with an asterisk above the box plot.

Figure 5. Scatterplots for performance on HINT-C sentences in semidiffuse noise with speech presented at 0°. Symbol shapes represent each participant and are consistent across listening conditions. Horizontal lines represent mean performance for each of the listening conditions.

Table 1.

Participant Demographic Information

Participant	Age (yr)	Age at 1st CI (yr)	Age at 2nd CI (yr)	Yr btw CIs	Years Exp 1st CI	Years Exp 2nd CI	1st CI Ear	Implants	Processors
1	9.1	0.9	3.7	2.8	8.3	5.5	R	Cochlear	Freedom
2	7.9	2.5	3.4	0.9	5.5	4.6	R	Cochlear	Freedom
3	7.5	0.9	1.8	0.9	6.5	5.7	R*	AB	Harmony
4	14.1	1.7	9.2	7.5	12.4	4.9	L	Cochlear	CP810
5	11.5	2.3	6.6	4.3	9.2	4.9	R	Cochlear	CP810
6	9.4	7.3	7.3	0.0	2.1	2.1	SIM	Cochlear	CP810
7	6.8	4.9	5.2	0.4	2.0	1.6	R	Cochlear	CP810
8	10.3	2.8	4.7	1.9	7.5	5.7	R	Cochlear	CP810
9	11.9	2.3	6.6	4.3	9.6	5.3	L	Cochlear	CP810
10	9.5	1.2	3.7	2.5	8.3	5.8	R*	Cochlear	CP810
11	6.3	1.6	2.2	0.7	4.8	4.1	L	Cochlear	CP810
12	10.3	6.8	8.0	1.2	3.5	2.2	L	Cochlear	CP810
13	10.8	2.7	9.9	7.2	8.1	0.9	R	AB	Harmony
14	11.8	1.1	4.1	3.0	10.7	7.7	R	MED-EL	Opus2
Mean	9.8	2.8	5.5	2.7	7.0	4.4			
SD	2.2	2.1	2.5	2.4	3.1	1.9			

Notes: Participant demographic information including age at testing, age at implantation, years between CI surgeries, years of CI experience for each ear, the first CI ear, implant manufacturer, and implant processors. Those participants for whom the second CI ear yielded significantly better performance than the first CI ear are indicated by an asterisk in the column labeled "1st CI ear." btw = between; Exp = experience; SD = standard deviation.

Table 2.

Speech Recognition Performance (% correct) for BabyBio Sentences

Participant	Quiet			S_0N_0			S_0N_{1stCI}			S_0N_{2ndCI}		
	1st CI	2nd CI	Bilateral	1st CI	2nd CI	Bilateral	1st CI	2nd CI	Bilateral	1st CI	2nd CI	Bilateral
1	99.3	99.3	99.3	48.0	23.4	47.0	31.5	63.6	70.1	77.3	27.0	83.7
2	74.8	68.9	72.3	40.0	18.5	41.7	18.0	37.5	54.3	52.2	15.3	48.2
3	96.9	84.6	95.0	31.4	54.7	60.4	44.8	62.8	71.0	84.3	30.7	60.4
4	94.0	92.0	99.0	10.6	18.0	60.3	14.9	23.4	55.0	33.1	0.0	57.0
5	83.0	71.5	85.0	55.6	58.4	57.0	51.7	71.4	65.2	64.8	58.6	65.0
6	83.7	75.6	90.3	42.7	14.9	57.2	21.2	39.7	56.0	61.7	29.0	60.0
7	66.7	70.0	78.0	49.7	43.0	51.0	48.1	67.9	66.1	68.7	60.3	69.3
8	92.6	88.6	88.5	51.7	54.7	61.2	43.1	90.0	87.9	65.6	19.5	61.0
9	79.0	17.0	76.1	56.2	0.0	60.3	70.2	0.0	75.2	81.4	0.0	85.0
10	97.8	97.9	100.0	32.6	46.0	57.3	29.2	94.5	97.1	38.1	20.0	61.0
11	65.7	67.6	71.9	56.3	62.1	62.1	46.9	62.0	52.3	70.5	55.2	55.5
12	63.6	18.4	69.8	55.3	21.2	50.3	50.0	21.4	57.1	72.4	12.9	58.5
13	97.0	75.8	98.0	65.3	12.6	70.6	72.8	52.5	86.6	87.5	8.0	87.5
14	96.0	88.0	98.0	54.0	48.0	58.0	47.0	75.0	70.0	79.0	35.0	79.0
Mean	85.0	72.5	87.2	46.4	34.0	56.7	42.1	60.2	68.9	66.9	31.6	66.5
Median	88.2	75.7	89.4	50.7	33.2	57.7	45.9	63.2	68.1	69.6	28.0	61.0
SD	13.1	25.5	11.5	14.1	20.4	7.2	17.6	16.3	13.9	27.0	20.1	12.4

Notes: Speech always presented from the front. Quiet = no babble. SD = standard deviation.