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Sound localization skills in children who use bilateral cochlear implants and in children with normal acoustic hearing

Tina M. Grieco-Calub, PhD and
Waisman Center, University of Wisconsin-Madison

Ruth Y. Litovsky, PhD
Department of Communicative Disorders and Waisman Center, University of Wisconsin-Madison

Abstract

Objectives—To measure sound source localization in children who have sequential bilateral cochlear implants (BICIs); to determine if localization accuracy correlates with performance on a right-left discrimination task (i.e., spatial acuity); to determine if there is a measurable bilateral benefit on a sound source identification task (i.e., localization accuracy) by comparing performance under bilateral and unilateral listening conditions; to determine if sound source localization continues to improve with longer durations of bilateral experience.

Design—Two groups of children participated in this study: a group of 21 children who received BICIs in sequential procedures (5–14 years old) and a group of 7 typically-developing children with normal acoustic hearing (5 years old). Testing was conducted in a large sound-treated booth with loudspeakers positioned on a horizontal arc with a radius of 1.2 m. Children participated in two experiments that assessed spatial hearing skills. Spatial hearing acuity was assessed with a *discrimination* task in which listeners determined if a sound source was presented on the right or left side of center; the smallest angle at which performance on this task was reliably above chance is the minimum audible angle. Sound localization accuracy was assessed with a *sound source identification* task in which children identified the perceived position of the sound source from a multi-loudspeaker array (7 or 15); errors are quantified using the root-mean-square (RMS) error.

Results—Sound localization accuracy was highly variable among the children with BICIs, with RMS errors ranging from 19°–56°. Performance of the NH group, with RMS errors ranging from 9°–29° was significantly better. Within the BICI group, in 11/21 children RMS errors were smaller in the bilateral vs. unilateral listening condition, indicating bilateral benefit. There was a significant correlation between spatial acuity and sound localization accuracy (R^2=0.68, p<0.01), suggesting that children who achieve small RMS errors tend to have the smallest MAAs. Although there was large intersubject variability, testing of 11 children in the BICI group at two sequential visits revealed a subset of children who show improvement in spatial hearing skills over time.

Correspondence to: Tina M. Grieco-Calub, Northern Illinois University, School of Allied Health and Communicative Disorders, DeKalb, IL 60115, Phone: (815) 752-8389, Fax: (815) 753-9123, tgriecocalub@niu.edu.

Short Summary: This study aimed to document spatial hearing skills in 21 children (5–14 years old) who had 3–28 months of experience with sequential bilateral cochlear implants (BICIs). Children were centered in front of a horizontal arc, with speakers located from ±70° at 10° intervals, and asked to identify the location of an auditory stimulus on two spatial hearing tasks: right-left discrimination (quantified by minimal audible angle) and sound source identification (quantified by the root-mean-square error). Although there was large individual variability in performance, results showed emerging spatial hearing skills in a subset of children who use sequential BICIs.

Conclusions—A subset of children who use sequential BICIs can acquire sound localization abilities, even after long intervals between activation of hearing in the first- and second-implanted ears. This suggests that children with activation of the second implant later in life may be capable of developing spatial hearing abilities. The large variability in performance among the children with BICIs suggests that maturation of sound localization abilities in children with BICIs may be dependent on various individual subject factors such as age of implantation and chronological age.

Keywords

bilateral cochlear implants; children; sound localization; spatial hearing

Introduction

The practice of providing deaf individuals with bilateral cochlear implants (BICIs) has been steadily increasing during the last decade. This clinical trend has emerged as a response to the fact that postlingually-deafened individuals using unilateral CIs continue to have difficulty functioning in complex listening situations. Overall, CI candidates who receive BICIs experience improved speech understanding, especially in the presence of interfering stimuli, as well as improved ability to localize sound sources in space (i.e., *spatial hearing*), both in ideal and complex listening situations (Tyler et al., 2002; van Hoesel and Tyler, 2003; Litovsky et al., 2004; Litovsky et al., 2006c; Litovsky et al., 2009; Neuman et al. 2007, Nopp et al., 2004; Mok et al., 2010).

Evidence for functional benefits from BICIs on spatial hearing abilities in postlingually-deafened adults has led to an increase in the number of children also receiving BICIs. Among this population of children are those who received one implant at a young age and a second implant after having one or more years of experience with the first (i.e., *sequential* BICIs). In contrast to children who grow up with normal acoustic hearing, children who are deaf and are fitted with sequential BICIs have a unique auditory experience that includes early onset of auditory deprivation, followed by a variable duration of unilateral input after activation of their first implant, and subsequent bilateral input after activation of the second implant. As a result, children with sequential BICIs may not gain access to bilateral acoustic information until they are a few years old. Since a number of auditory skills that exploit bilateral input, such as spatial hearing, develop during the first few years of life (Litovsky, 1997; reviewed in Litovsky & Ashmead, 1997), there is an open question regarding the extent to which these skills can mature in children with sequential BICIs.

A number of studies have begun to address this issue. Litovsky et al. (2006a, 2006b) documented the emergence of right-left discrimination abilities in two groups of children using either BICIs or bimodal hearing [i.e., CI in one ear and hearing aid in the opposite ear (CIHA)]. Using a two-alternative-forced-choice (2-AFC) task, children were asked to locate a sound source to the right or left side of midline (0°). Performance was quantified by calculating the *minimum audible angle*, which is the smallest angle that can be discriminated on a left-versus-right discrimination task (MAA; Mills, 1958). In the Litovsky et al. studies, children had smaller MAA thresholds when using bilateral devices (BICIs or CIHA) than when using their first CI alone, although in the bilateral listening condition, the BICI group had smaller MAA thresholds than the CIHA group. An additional finding was that the MAA thresholds improved over time in a subset of these children (Litovsky et al., 2006a), suggesting that input provided by BICIs is sufficient to promote the refinement of spatial hearing. These results are consistent with other studies showing that, in sequentially-implanted children, right-left discrimination for a small set of source locations tested (±90° or ±30°) was better when BICIs were used than when a unilateral CI was used (Steffens et al., 2008; Beijen et al., 2007; Galvin et al., 2008). In addition, similarly aged children with bimodal fittings (i.e., CI in one ear and a hearing aid in the other ear) showed a functional benefit when using two devices versus their CI alone (Beijen et al., 2009).

Although some of the experimental methods were modified across studies of spatial hearing in children with sequential BICIs, a common thread was the utilization of the right-left discrimination (i.e., 2-AFC) task to determine children's *spatial acuity* as quantified with MAA. Although one can use this measure to evaluate children's ability to discriminate between two source locations, it provides little information regarding the ability to identify the specific location of sound sources (i.e., *localization accuracy*). In support of this idea, Moore et al. (2008) concluded that spatial acuity and localization accuracy are not directly predictable from one another. In addition, it is unclear as to whether the neural mechanisms underlying each skill are similar. This raises the possibility that MAA may not appropriately represent the functional spatial hearing skills necessary to navigate one's auditory environment that contains a myriad of sound sources. Alternatively, if a relationship between spatial acuity and localization accuracy can be made, the use of right-left discrimination to estimate functional spatial hearing skills may be more clinically feasible.

The purpose of this study was to extend our prior work on outcomes in children who have sequential BICIs to more complex tasks of sound source identification, rather than the simpler task of discrimination. Localization accuracy was tested with either a 15-AFC or 7-AFC task, in which loudspeakers were positioned in the horizontal plane at locations ranging from ±70°. Performance was quantified with a standard method of calculating root-mean-square (RMS) error, which is computed from the deviations on each trial of the judged location to the actual source location. To determine if children received a benefit from bilateral input, the task was performed twice at each visit: once while using both implants and once while using the first implant alone. Based on the growing body of sound localization data from adults who use BICIs, we hypothesized that children too would have smaller RMS errors when using both implants than when using their first implant alone. A second hypothesis was that, regardless of task, spatial hearing abilities would continue to improve with longer durations of bilateral experience. The second hypothesis was tested by bringing a subset of children back to the lab for a second round of testing at least 7 months after the first testing protocol was completed.

Methods

Subjects

Children with BICIs—Twenty-one (21) children between 5–14 years of age who received sequential BICIs participated in this study. All children had a history of bilateral sensorineural hearing loss, either identified at birth (N=11) or following some experience with acoustic hearing (N=10). History of acoustic experience was provided by the children's parents and defined as some level of usable hearing (with or without the use of hearing aids) prior to deafness and implantation. Children were free from other medical complications. Despite active recruitment of participants with all three cochlear implant device types, of the 21 children, 17 used Cochlear devices, 3 used Advanced Bionics devices, and 1 used the Med-EL Corp. device. The duration of bilateral experience ranged from 3–28 months. All children were enrolled in, or graduated from, aural rehabilitation programs with an auditory-verbal emphasis. A more comprehensive description of participants can be found in Table 1. Consistent with previous reports on a subset of these children (Litovsky et al., 2006b), participant codes are in the format CIXX, representing the order in which they enrolled in the research program. The goal of this method is to track participant performance across different reports produced through the research program of the Binaural Hearing and Speech lab.

Due to the limited number of young children with sequential bilateral cochlear implants in the greater Madison, WI area, children were recruited from across the country through their audiologists, surgeons, or self-referrals. This type of recruitment tends to result in a biased sample, since those families who enrolled in the study were highly motivated to partake in research, and often traveled long distances to Madison, WI to participate in the studies.

Children typically spent two days working in the laboratory, during which they participated in a number of tasks including right-left discrimination, speech-in-noise, and sound source identification under bilateral and unilateral listening modes. Ten of the children reported here have been cited in previous reports that focus on performance on other tasks associated with this research program (Litovsky et al., 2006a; Litovsky et al., 2006b). In addition, 11 of the 21 children participated in the research program at two sequential visits following the activation of their second CI.

Children with normal acoustic hearing—Seven (7) children who are typically-developing participated in the study. Children had no history of hearing loss, middle ear problems, or other developmental delays per parental report. Children in this normal hearing (NH) control group were recruited at 5 years of age (5.5 ± 0.1 years) since their performance was expected to be representative of NH children of the equivalent age to the youngest participants in the cohort of children who use BICIs.

This study was approved by the institutional review board of the University of Wisconsin-Madison.

Experimental Set-up

Testing was conducted in a sound-treated booth (IAC, reverberation time of 250 ms) containing a semicircular array of 15 matched loudspeakers positioned at 10° intervals in the frontal hemifield (–70° to 70°). The loudspeakers were at ear level and at a distance of 1.2 m from the center of the listener's head. Children sat on a chair, facing the front loudspeaker (0°). A computer monitor placed underneath the front loudspeaker was used as part of the computerized experimental paradigm (see *Procedure*). Each loudspeaker was assigned a child-friendly visual icon which served as that loudspeakers' reference during the task (see *Procedure*). Hardware included a Tucker-Davis System III (Tucker-Davis Technologies, Alachua, Fla) with a multiplexer for loudspeaker selection and a PC host. Customized software for stimulus presentation and data collection was written in Matlab programming language.

Stimuli

At the outset of this study, localization data were collected using noise stimuli (i.e., 3 bursts of 25 ms pink noise with 5 ms rise/fall times and 250 ms interstimulus interval; Litovsky et al., 2004). After testing a few children with this stimulus (including CIAB and CIAC who are reported here), it was determined that a speech stimulus was more effective. Therefore, for the other 19 children, the stimulus was the spondaic word, "baseball", recorded with a male voice at a sampling rate of 44 kHz and stored as .wav files.

Unless specified in the text or figures, stimulus levels on all tasks averaged 60 dB SPL, and were randomly varied between 56–64 dB SPL (roved by ±4 dB) from trial to trial, in order to minimize the extent to which overall level cues would be relied on for localization. The rove value was selected to be consistent with prior studies in this field (e.g., Nopp et al., 2004; van Hoesel, 2004; Litovsky et al., 2006; Litovsky et al., 2009) also concerned with keeping stimulation levels within the meaningful dynamic range of cochlear implant processors. Also consistent with prior studies is the fact that the microphone is not placed in the ear canal, but rather behind the ear, although this particular configuration appears to maintain inter-aural level cues that arise primarily from shadowing of the signal by the head (van Hoesel, 2004).

Procedure

The CI speech processors of the participants were programmed by their audiologists prior to their visit. No attempt to modify the CI programs was made in the laboratory. However, for each child, we verified that a sound source presented from the front loudspeaker (0°) was perceived to be emanating from that location.

Testing was conducted as described previously (Litovsky et al., 2006a). Briefly, customized, interactive computer software was developed for stimulus presentation and data collection. The software also incorporated a computerized puzzle game to maximize each child’s motivation. After each trial, a missing puzzle piece appeared on the front monitor so that children appeared to be “building the puzzle” as they progressed through the experiment. In addition, children received stickers and small prizes after series of trials and at the end of each day of participation.

At each visit, children’s spatial acuity was assessed using a right-left discrimination task and localization accuracy was assessed using a sound source identification task:

Right-Left Discrimination—Children completed the right-left discrimination task with their BICIs (i.e., bilateral condition). For each child, this two-alternative-forced choice (2-AFC) task was completed prior to the sound source identification task. On each trial, after children were oriented to the front (0°), a speech stimulus was presented to the right or left of midline at equivalent angles that were varied in increments of 10° (ranging from ±70° to ±10°). Children who had ceiling effects at ±10° repeated the task with speakers at ±2.5°and ±5°. Children used the computer mouse to select icons on the screen indicating the perceived side of the sound source. After each response, children received feedback such that the icon for the correct side blinked on the monitor screen. Source direction (right/left) varied randomly, and angular separation of the right and left speakers from center was fixed during blocks of 20 trials. Angle size varied from block to block depending on the children’s behavior on the task. If overall performance yielded 75% correct within a block of 20 trials, the angle was decreased; otherwise the angle was increased. To eliminate fatigue on the part of each participant, the goal was to approach the estimated threshold efficiently. To accomplish this, decisions regarding the step size between blocks of trials, leading to increased or decreased angles, were based on similar rules to those used in adaptive procedures (e.g., Litovsky, 1997; Litovsky & Macmillan, 1994). For example, if a child scored >75% at a test angle, the angle was decreased by 30°; if the child scored <75%, the angle was increased by 10°. The minimum audible angle (MAA), or the smallest angle at which listeners can discriminate a right-versus-left sound source (Mills, 1958), was used to quantify spatial acuity. MAA thresholds for each listening mode (bilateral and unilateral) were defined as the smallest angle at which performance reached 70.9% correct. The angle that yielded 70.9% correct was linearly extrapolated between the two adjacent angles that yielded performance above and below 70.9% correct respectively (Litovsky et al., 2006a; 2006b).

Sound Source Identification—On each trial, children were asked to select the specific loudspeaker from which the stimulus was presented. Children used the computer mouse to select icons on the screen that corresponded to the perceived location of the sound source. For a few of the younger children, the experimenter entered the child’s verbal response into the computer. After each response, children received feedback such that the correct-location icon blinked on the screen.

Children participated in either a 7- or 15-alternative-forced choice (7-AFC or 15-AFC, respectively) task. Loudspeaker separation was 20° for the 7-AFC task and 10° for the 15-AFC task. For the 7-AFC task, the visual icons associated with the speakers that were not in use (±10°, ±30°, ±50°, ±70°) were removed.

Pilot testing suggested that successful completion of the 150 trials in the 15-AFC task in the BICI group was dependent on performance on the right-left discrimination task. Thus, for this study, children who were assigned to the 15-AFC task had MAAs of less than 30 degrees (an angle deviation that is 2 speaker positions greater than the smallest speaker separation on the 15-AFC task); all other children participated in the 7-AFC task. To track performance over time, loudspeaker separations were matched on two sequential visits for each child, regardless of changes of spatial acuity. Stimuli were presented 10 times from each location, resulting in 70–150 trials per child, with the exception of one child: CIAE completed only 5 trials per loudspeaker due to fatigue. All children in the NH group participated in a 15-AFC task. The root-mean-square (RMS) error between the azimuth of the stimulus location and the listener's response was used to quantify localization accuracy. Chance performance ± one standard error unit was calculated to be 61.1° ± 3.6° for the 15-AFC task and 56.6° ± 4.6° for the 7-AFC task (Hartmann et al., 1998).

Data from this task was also used to calculate three other measures of performance (Table 2). Responses for target locations ranging from 0° to −70° and from 0° to 70° were used to determine the RMS error and correlations for the left and right hemifields, respectively. Responses for target locations ranging from −10° to −70° and from 10° to 70° were used to calculate the percentage of correct responses for the left and right hemifields, respectively.

To calculate bilateral benefit, children completed the sound source identification in two separate blocks: first when using their BICIs (i.e., bilateral condition) and then again when using their first CI alone (i.e., unilateral condition). This decision was made based on the hypothesis that performance would be better in the bilateral condition, and thus limiting any frustration with the task in the unilateral condition. There are two disadvantages of this paradigm. For example, any training effects would improve performance in the unilateral condition. Alternatively, the fact that the unilateral condition is not a natural listening condition for these children may have inflated the bilateral benefit.

Results

Sound source identification

To establish a baseline of performance on the sound-source identification task, a group of typically-developing, 5-year-old children with normal acoustic hearing (NH group) was evaluated. Individual scatter plots of their localization accuracy and RMS errors are plotted in Figures 1A and Figure 2A, respectively. All children had RMS errors that were less than 30° (range: 8.9°–29.2°).

In contrast to the NH group, there was a larger range of RMS errors (19°–56°) among children who use BICIs in the bilateral condition under similar experimental settings (Figures 1B and 2B). Visual inspection of the individual scatter plots (Figure 1B) revealed large variability in sound source identification skills within the BICI group. Despite the variability, all but three children (CIAT, CIAG, CIAB) performed at least one standard error unit above chance levels on this task. To better quantify performance of the children in the BICI group, the following statistics are listed in Table 2: Percentage of responses in the correct hemifield (chance performance is 50%; two standard deviations above chance is 58% for the 15-AFC task and 62% for the 7-AFC task), RMS error for each hemifield, and correlation of target and responses within each hemifield.

Although there was a wide range of bilateral RMS errors among children in the BICI group, the individual scatter plots and additional analyses revealed three primary groups of children based on their performance. Group A included six children who performed similarly to the NH group according to the following criteria: First, the percentage of correct responses in each hemifield was within two standard deviations of the NH group average (Left: 92% ± 5.4%, Right: 89% ± 7.6%, mean ± SD, N=7). Second, correlations between target locations and responses were significant. Third, bilateral RMS errors ranged from 19.1° to 27.9° which fell within two standard deviations of the NH group average (18.3° ± 6.9°, N=7). Group B included 8 children who identified the correct hemifield of the target at better than chance performance, but varied in their ability to identify the target location within each hemifield which resulted in a lack of significant correlation between the targets and responses. Their bilateral RMS errors ranged from 32.8° to 42.5° which were larger by more than two standard deviations of the NH group average. Finally, Group C included 7 children who showed little ability to perform the sound source identification task. Responses were randomly distributed among the correct/incorrect hemifield in at least one hemifield for 3 children and in both hemifields for 4 children. In addition, few of their responses approximated the diagonal line as evidenced by both a lack of significant correlation between target locations and responses within each hemifield and bilateral RMS errors ranging from 43.5° to 66.8°.

To compare performance between the BICI and NH groups, an unequal N, between-subjects analysis was performed. CIAB and CIAC were removed from this analysis since they localized a different auditory stimulus than the NH group (see *Methods*, *Stimuli*). On average, the BICI group had significantly poorer localization accuracy (37.4° ± 11.0°, N=19) than the NH group [18.3° ± 6.9°, t(24)=4.2, $p<0.001$]. It is interesting to note, however, that six (6) of the 19 children in the BICI group had RMS errors that were within the range of those of the NH group (Figure 2B). While RMS error is a good tool for condensing performance down to a single metric, it is clearly not reflective of the various trends in the raw data. A careful inspection of individual subjects' responses in Figure 1 suggests that RMS errors of similar values can be obtained for response profiles that are somewhat different. For example, the RMS of approximately 30° seen in several CI users resulted from different error types than that seen in the worse-performing NH subject (NH7, Figure 1A). While the NH participant generally responded near the correct loudspeaker location, this child had a few large errors, which brought up the average error calculated. In contrast, the CI users with a similar or lower RMS (Figure 1B, top row) all had more scatter in their data. The source of this scatter is unclear; however, possibilities include spatial hearing abilities that are less well established, localization blur or uncertainty on the part of the participant.

In an attempt to identify predictors of localization accuracy in the BICI group on conditions with both CIs worn, a multivariate linear regression analysis was completed. Initially, six variables were used in the regression model: the children's age at visit, age at first implant activation, age at second implant activation, history of acoustic hearing, duration of unilateral implant use, and duration of bilateral implant use were included in the regression model. Because of high intercorrelations among the three age variables, two of those variables were removed from the regression model. The analysis produced a significant result [F(4,14)=3.1, $p=0.05$] and revealed a significant effect of age at second implant activation [t(14)= −3.4, $p<0.01$; Table 3). As noted above, however, age of second implant activation was highly intercorrelated with the children's age at visit and age at first implant activation. This observation suggests that, although the age at second implant activation may be a predictor of localization accuracy, its effects cannot be separated from the possible effects of chronological age and/or age at first implant activation.

Relationship between right-left discrimination and sound source localization

Previous work from our research program has suggested that right-left discrimination abilities (another measure of spatial hearing that is quantified with the minimum audible angle (MAA)), typically emerge within 12 or more months following activation of the second implant in children who have sequential BICIs (Litovsky et al., 2006a; Litovsky et al., 2006b). Based on the observation that the majority of children were able to identify the correct hemifield of the target location significantly above chance (i.e., good spatial acuity), but continued to have difficulty identifying the specific location (i.e., poor localization accuracy), the next objective of the study was to determine a relationship, if any, between the two measures.

Figure 3 illustrates the relationship between spatial acuity and localization accuracy for the 19 children in the BICI group who localized a speech stimulus. There was a moderate correlation between the two measures [R^2=0.68; F(1,16)=33.3, p<0.001], suggesting that the best performers on the right-left discrimination task were the best performers on the sound source identification task. Closer inspection of the data, however, revealed a wide range of RMS errors (19.1°–44.1°) for children who had relatively small MAAs (less than 20°). This finding suggests that when spatial acuity is poor (as reflected by a large MAA), localization accuracy is expected to be poor as well (as reflected by a large RMS error). However, when spatial acuity is good, children may exhibit wide-ranging localization accuracy.

Effect of Unilateral experience

One of the objectives of the study was to determine if there is a bilateral benefit on the sound source identification task. To evaluate this, children completed the sound source identification task with their first CI alone, and their performance was compared to that from the bilateral condition (Figure 2A; Figure 4, *circles*). Figure 4 illustrates the individual RMS errors for the unilateral CI condition (*squares*) in which all but one child (CIAP) performed significantly above chance levels. A repeated-measures, within subjects t-test of the entire BICI cohort (N=21) showed that localization accuracy in the unilateral listening condition was significantly poorer than the localization accuracy in the bilateral listening condition [t(20)=−3.3, p=0.003]. Consistent with this finding, an unequal-N between subjects analysis revealed the RMS errors of the children in the BICI group who localized a speech stimulus in the unilateral condition (45.6° ± 7.1°, N=19) to also be significantly poorer than the RMS errors reported above for the NH group [8.3° ± 6.9°, N=7, t(24)=8.7, p<0.001].

To better quantify a functional benefit of using bilateral implants for each child, bilateral benefit was defined as achieving RMS errors in the bilateral condition that were greater than the RMS errors for the unilateral CI condition by two standard error units (i.e., 7.3° for the 15-AFC task and 9.3° for the 7-AFC task; Hartmann et al., 1998). Using these criteria, closer inspection of individual performance revealed that eleven of the children exhibited significantly better performance when using both CIs compared with the single-CI condition; ten children did not perform significantly different in the two listening conditions. A linear regression analysis was completed in attempt to identify possible predictors of unilateral performance. The children's age at visit, age at first implant activation, age at second implant activation, history of acoustic hearing, duration of unilateral implant use, and duration of bilateral implant use were included in the regression model. None of these variables were found to be significant predictors of RMS errors in the unilateral condition [F(1,14)=1.04, p=0.42].

Emergence of spatial hearing abilities over time

To determine if sound localization abilities mature with increasing bilateral experience, 11 children were re-tested 7–21 months after the first testing. At each visit, children participated in the right-left discrimination task when using their BICIs. In addition, they were retested in the sound source identification task both in the bilateral and unilateral (first-CI) listening conditions. Experimental conditions were matched between the two visits so that changes in performance would be free from protocol changes (e.g., target stimulus or number of loudspeakers) and presumably reflect changes in each child's ability to perform the tasks. Figure 5 illustrates RMS errors from individual children using their BICIs (*circles*) and their first CI alone (*squares*) as well as MAAs from these same children using BICIs (*triangles*).

Although there was large individual variability in performance with BICIs over time, preliminary observations revealed three groups of children: *1*) children who had large RMS errors (e.g., >50°) at both visits (*top row*), *2*) children who showed a reduction of RMS errors (i.e., improvement) by 10° or more between visits 1 and 2 (*middle row*), and 3) children who had relatively small RMS errors (e.g., ≤ 30°) at both visits (*bottom row*).

Grouping children by both initial performance and change in performance over time led to a number of notable preliminary observations. For example, children who had large RMS errors with their BICIs on both visits (N=3; Figure 5, *top row*) tended to have large RMS errors with their first CI alone on both visits as well. Two out of three of these children, however, showed an improvement in bilateral MAA. Children who had improvements of 10° or more (i.e., >2 standard error units) in localization accuracy with their BICIs on visit 2 had similar improvements in spatial acuity (N=4; Figure 5, *middle row*). Although there was a concomitant reduction in the RMS error with the first CI alone for two of the four children, RMS errors continued to be larger in the unilateral condition. Finally, children who had RMS errors between 20°–30° on visit 1 (N=4; Figure 5, *bottom row*) all had small reductions in RMS errors on visit 2. Three out of four of these children had a concomitant improvement in bilateral MAA. Changes in performance were not observed, however, for three out of four of the children when they used their first CI alone.

Discussion

This is among one of the first studies to measure sound source localization accuracy using a large array of loudspeakers in children who use sequential bilateral cochlear implants (BICIs). Of the 21 children in this study, ten had RMS errors of ≤ 40° when using BICIs, suggesting that these children have some degree of sound localization skills. In addition, all children had either significantly better or equivalent performance when using BICIs relative to the unilateral condition. This finding suggests, that even after long durations of unilateral CI use, exposure to bilateral auditory information can continue to promote, and in many cases improve, localization accuracy. These findings are consistent with previous data published by this lab (Litovsky et al., 2006a, 2006b; Godar and Litovsky, 2010) as well as others (e.g., Galvin et al., 2008; Beijen et al., 2007). It is important to note, however, that a control group who uses a unilateral CI exclusively was not included in this study. As a result, we are unable to determine a change in performance on the sound localization tasks over time during which a single device was exclusively used.

This study is also among the first to provide benchmark data from 5-year-old children who have normal acoustic hearing on a 15-AFC sound source identification task. Performance of these children was poorer than that typically seen in adults, suggesting that this skill is still emerging in young children with normal hearing. The results from this study were in slight conflict with data from a recent study by Van Deun et al. (2009). In the Van Deun et al. (2009) study, 5-year-old children who performed a similar sound source identification task had a median RMS error of 6°. This performance was significantly better than what was observed in the present study (18.3° ± 2.6°). It is important to identify the differences in experimental protocol between the two studies because they may explain the discrepancy. In the Van Deun study, children localized a 1-sec bell-ring in a 9-AFC task among loudspeakers that were placed at 15° intervals. In the present study, the stimulus was speech (“baseball”) and the number of potential sources was 15 (with a loudspeaker separation of 10°). Finally, a 5 dB intensity rove was used on each trial in the Van Deun study, whereas an 8 dB intensity rove was used in the present study. The task in this study was most likely more challenging, and the stimuli more difficult to localize compared with those in Van Deun et al’s (2009) study, resulting in overall poorer performance as well as a wider range of RMS errors in normal-hearing children.

Auditory deprivation and bilateral experience

A number of reports have sought to identify a relationship between the duration of auditory deprivation and developmental outcomes in children who use CIs. In other domains, such as language skills, there is an overall effect of early implantation. Oral language outcomes are generally better (e.g., Kirk et al., 2002; Wang et al., 2008; Nicholas & Geers, 2006) and neurophysiological markers of maturation are in the normal range (Sharma et al., 2005; Gordon et al., 2007) when children are implanted at an early age. Spatial acuity may also depend on early stimulation, but what is unclear is whether the key factors are early age of implantation or early exposure to bilateral stimulation. As reported by Grieco-Calub et al. (2008), many young BICI users who receive their second CIs before the age of 29 months have age-appropriate MAAs, suggesting that age of bilateral implantation may result in better outcomes. Recent evidence from Van Deun et al. (2010) supports this possibility.

A clinically relevant issue related to this study was whether sound localization skills would be present in children who experienced long periods of unilateral CI use prior to activation of their second CI. The results of the current study suggest that bilateral implantation later in childhood can promote spatial hearing, although there is large individual variability in performance. Some children (e.g., CICD, CIAQ, CIBJ) appear to be performing at a level that is near that of their peers who have normal acoustic hearing, whereas other children (e.g., CIBC, CIAT, CIAB, CIAG) perform close to or at chance levels with their BICIs. It is important to note here that poor performance on the localization ability is not a reflection of lack of the children's lack of understanding of the task, since substantial training and feedback was provided prior to initiation of testing.

A noteworthy observation is that among the children in the BICI group who performed similarly to their NH peers (e.g., Group A), all but one (CIAQ) had a history of acoustic experience. Although history of acoustic experience was not a significant predictor of performance on the sound source identification task, there are caveats that need to be considered. First, due to the cross-sectional nature of the study, sound source localization skills may still be emerging in these children. Therefore, the extent to which acoustic experience can predict the maximum performance of these participants cannot be determined at this time. Second, the duration and amount of acoustic hearing that the children experience was not quantified for the purpose of this study. A more detailed description of acoustic hearing for these children may have elucidated its role in these results. The observation, however, that the children in the BICI group with the smallest RMS errors had some acoustic hearing prior to implantation suggests that this experience may provide some benefits. For example, exposure to interaural timing and level cues during the age when these skills are developing (Litovsky, 1997) may result in better outcomes following implantation. Nicholas and Geers (2006) found a similar benefit of early acoustic experience on language outcomes in children who use cochlear implants. Further studies are needed to investigate this issue.

Relationship between right-left discrimination and sound source identification

The relationship between right-left discrimination abilities on a 2-AFC task and sound source identification in a multi-source task (7- or 15-AFC) may provide insight into the emergence of spatial hearing abilities in children who use sequential BICIs. As illustrated in Figure 5, MAAs tended to be smaller than RMS errors, which is consistent with reports in the literature regarding sound localization abilities in normal hearing adults. For instance MAAs are generally 1–5°, depending on the stimulus and exact task (e.g., Litovsky and Macmillan, 1994;Mills, 1958). Contrary to other reports (Moore et al., 2008), results from this study revealed a moderate correlation between right-left discrimination (i.e., spatial acuity) and sound source identification (i.e., sound localization accuracy). Consistent with the findings of Moore et al. (2008), however, when MAA is small, spatial acuity in a 2-AFC task cannot predict localization accuracy in a multi-source task. The MAA is a measure of the extent to which listeners are able to perceptually separate between two distributions along a decision axis that contains information regarding source azimuth. Localization RMS errors on the other hand represent a measure of the deviation of response from the target position. While the same azimuthal-related decision axis is involved, the decision is based on a more complex decision variable than selection between two distributions.

The present findings raise the possibility that precision with which right-left discrimination is made is a prerequisite for, and possibly even precedes, sound source localization skills in children who use sequential BICIs. Whether the two spatial hearing skills are mechanistically related is a topic of debate (Hartmann and Rakerd, 1989; Recanzone et al., 1998; Moore et al., 2008). Together with other findings using identical methods (Litovsky et al., 2006a; Godar and Litovsky, 2010), there is evidence to suggest that while spatial acuity typically emerges within 12 months of bilateral experience, localization accuracy may require more experience before emerging. Preliminary longitudinal data from 11 children in this study provide further support of this idea. Figure 5 reveals that improvements in localization accuracy could only be expected to occur in children who have very good spatial acuity or in children who show a concomitant improvement in spatial acuity. Longitudinal data over a number of visits from additional children are needed, however, before any conclusions can be drawn from data like these.

Prolonged unilateral experience

A number of children in this study experienced stimulation with a unilateral CI for a prolonged period of time prior to the activation of their second implant. Overall, there was a large range of unilateral CI experience (10–142 months). Although long periods of unilateral stimulation can disrupt binaural brainstem processing as measured with electric auditory brainstem response (EABR; Gordon et al., 2008), there is no evidence of disruption of localization accuracy in this study since durations of unilateral CI use did not predict unilateral RMS errors. This raises two possibilities. One is that the binaural processes that are assessed with EABR measures are not representative of the auditory processes used for sound source identification. Alternatively, children who use unilateral CIs for long durations of time might be capable of developing listening strategies that enable them to judge sound source locations in the auditory environment based on unilateral information alone. The results from this study provide support for the latter possibility. Consistent with this idea, some postlingually-deafened adults who received unilateral CIs have been shown to develop spatial hearing skills better than chance (Grantham et al, 2008). In contrast, postlingually-deafened adults who received simultaneous BICIs and who did not have the opportunity to listen with a single implant have been shown to perform poorly overall when using a single CI (e.g., Litovsky et al., 2009). Taken together, it appears that experience has a role in the establishment of sound localization abilities in CI users.

The acoustic cues that would be utilized under unilateral listening conditions are most likely overall level cues. In the present study, the intensity level was roved by 8 dB (±4 dB) from trial to trial to minimize the extent to which overall level cues would be relied on for localization. However, this amount of rove is smaller than the 20 dB needed to fully eliminate overall level cues at high frequencies. Thus, monaural level cues were likely available to, and utilized by, a number of the children.

Potential limitations of bilateral cochlear implants

Although postlingually-deafened adults and prelingually-deafened children appear to derive benefit from using BICIs, recent evidence suggests that these individuals may not have access to all available binaural cues. Individuals who have normal acoustic hearing use a number of binaural cues [e.g., interaural timing differences (ITDs) at low frequencies carrying fine-structure information and at high frequencies when envelope cues are available, as well as interaural level differences (ILDs)] and monaural spectral cues to determine the location of a sound source (reviewed in Bernstein, 2001; Blauert, 1997). Since the commercially-available CI speech processors function in isolation of one another and, therefore, do not coordinate the input to each auditory nerve, the use of BICIs, however, does not necessarily guarantee that binaural cues are available to listeners with electrical hearing. For example, the lack of coordination and independence of the internal clocks of the processors most likely lead to inconsistent transmission of ITDs that might exist between the envelopes of the left and right signals. In addition, the fact that fine-structure cues are discarded in the signal processing means that ITDs related to the fine structure are unavailable. Finally, because the microphone for many implant users is located above the pinna, rather than in the ear canal, spectral cues are probably unavailable. As a result, the most salient cue that is available to users of BICIs are ILDs. Consistent with this idea, postlingually-deafened adults rely more on ILDs than ITDs (Grantham et al., 2007; Seeber & Fastl, 2008; van Hoesel, 2004).

Implications

The increase in the number of children receiving a second implant demands that the process by which spatial hearing skills mature be understood. In response to this need, there has been a concomitant increase in the number of studies investigating the benefits from BICIs in children. At the same time, there are important considerations regarding the extent to which benefits from a hearing aid in the non-implanted ear can be attained. Although many of the children who use BICIs are able to localize sounds in their environment, it is still unclear what cues they are using to accomplish these tasks, particularly since the speech processors have difficulty providing access to coordinated timing information. In addition, aside from anecdotal data, it is still unknown as to how localization performance in laboratory correlates with localization in the world where listening environments are more complex but which contain more context such as speaker familiarity, relevance of the sound being localized, and knowledge of the listening environment. Future studies will need to address these issues.

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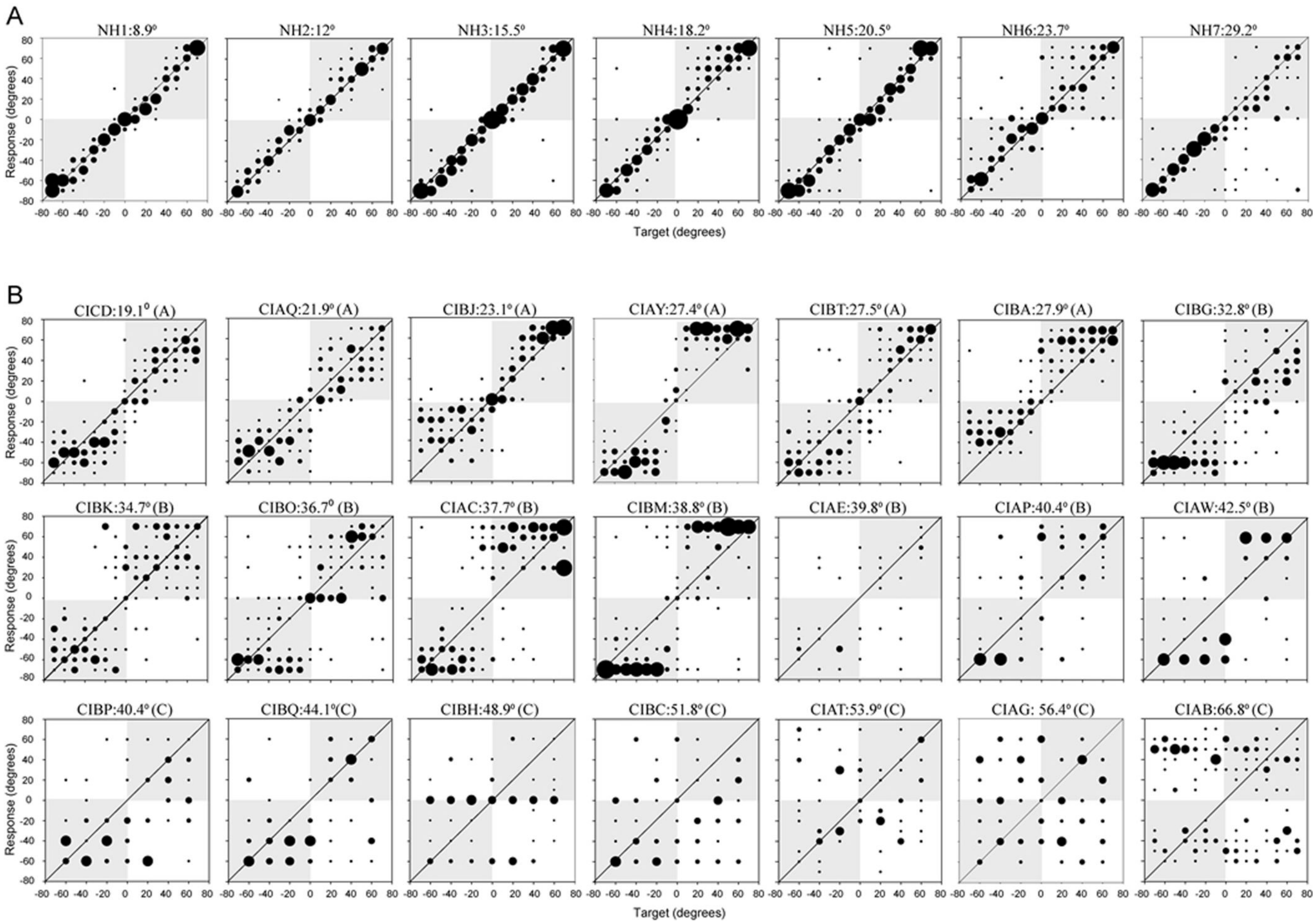

Figure 1.

Individual performance on the sound source identification task in the NH group (*A*) and the BICI group (*B*). The size of the dots represents the number of responses for a given target location. Larger dots reflect a greater number of responses. The diagonal line represents perfect performance. Letters in the parentheses indicate the subgroup that each child in the BICI group belongs to based on performance.

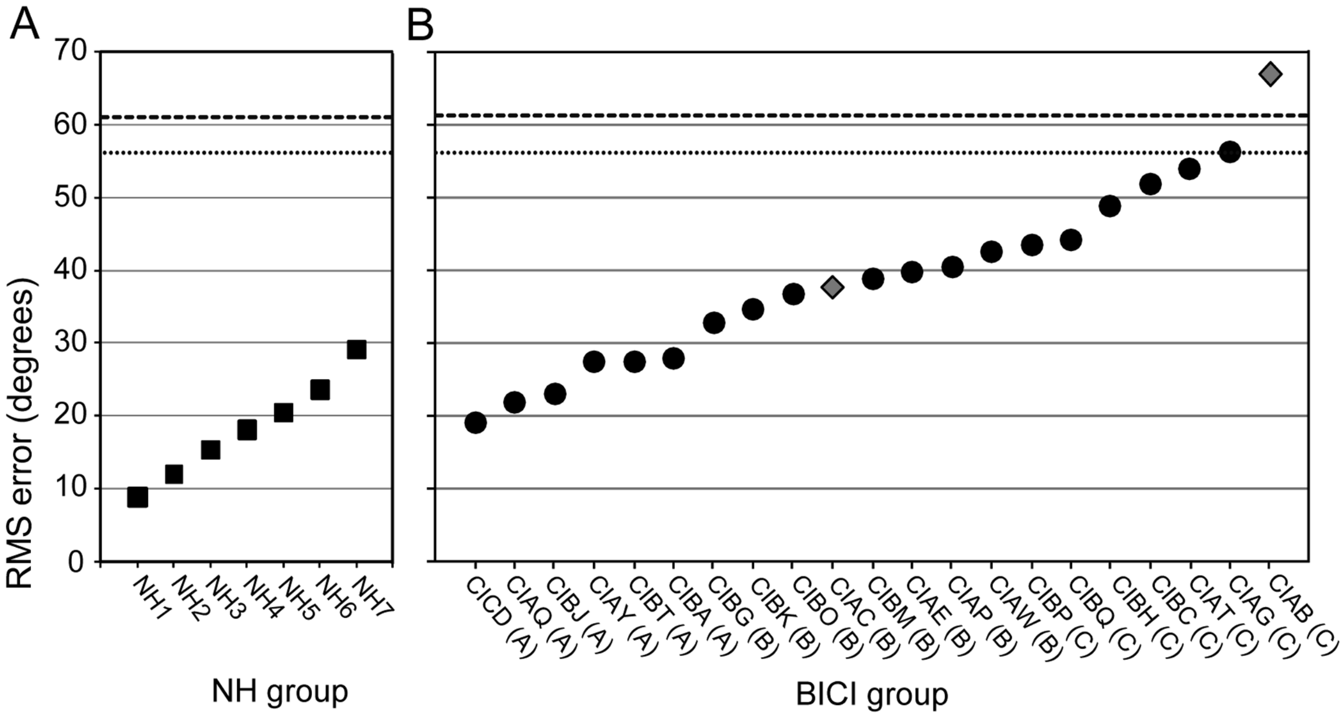

Figure 2.

Individual performance on the sound source identification task (as quantified by RMS error) for the NH group (*A*) and the BICI group when using both implants (*B*). In both panels, data are plotted along the x-axis from small RMS errors (better performance) to large RMS errors (i.e., poorer performance). Letters in the parentheses indicate the subgroup that each child in the BICI group belongs to based on performance. The gray diamonds represent the two children who were tested with the noise stimulus. The dotted line represents chance performance for the 7-AFC task and the dashed line represents chance performance for the 15-AFC task.

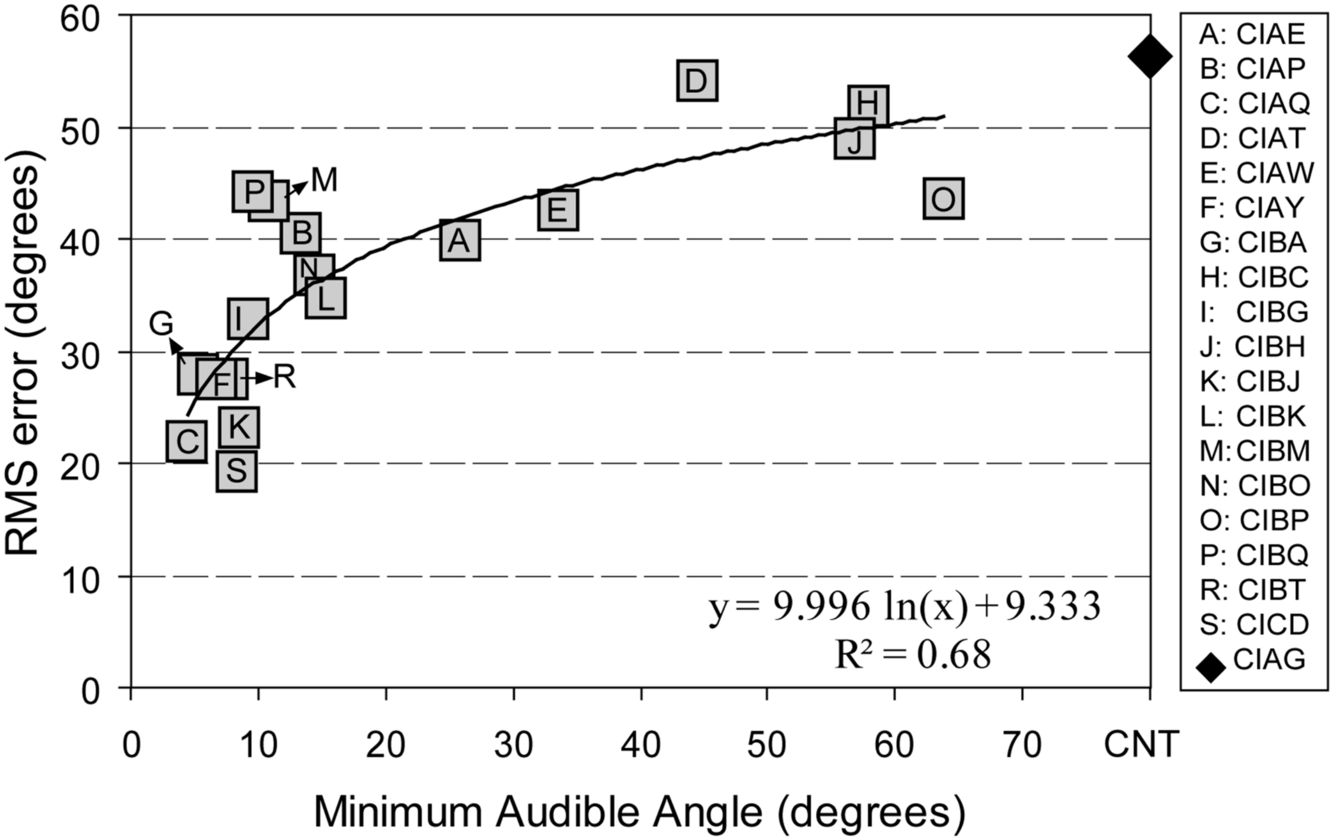

Figure 3.

Relationship between sound localization accuracy (as quantified by RMS error) and spatial acuity (as quantified by minimum audible angle). CNT: MAA could not be calculated because CIAG did not perform at above chance levels on the maximum angle separation (±70°).

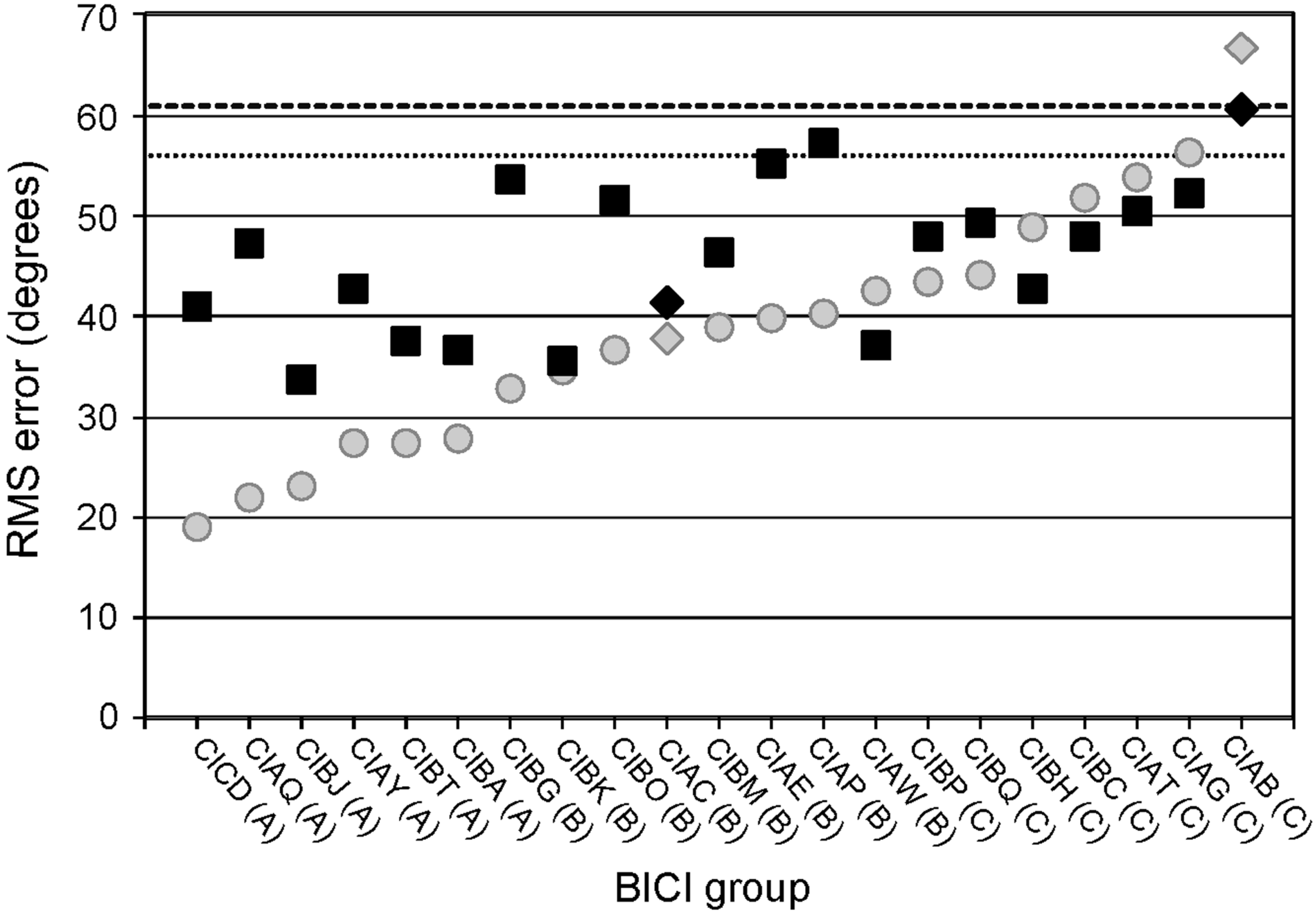

Figure 4.

Individual performance of the BICI group on the sound source identification task (as quantified by RMS error) when using a single CI (*squares*). Data from the bilateral condition (*circles*, from Figure 2B) are plotted for comparison. Data are plotted along the x-axis similarly as in Figure 2B. Letters in the parentheses indicate the subgroup that each child in the BICI group belongs to based on performance. The diamond symbols represent the two children who were tested with the noise stimulus. The dotted line represents chance performance for the 7-AFC task and the dashed line represents chance performance for the 15-AFC task.

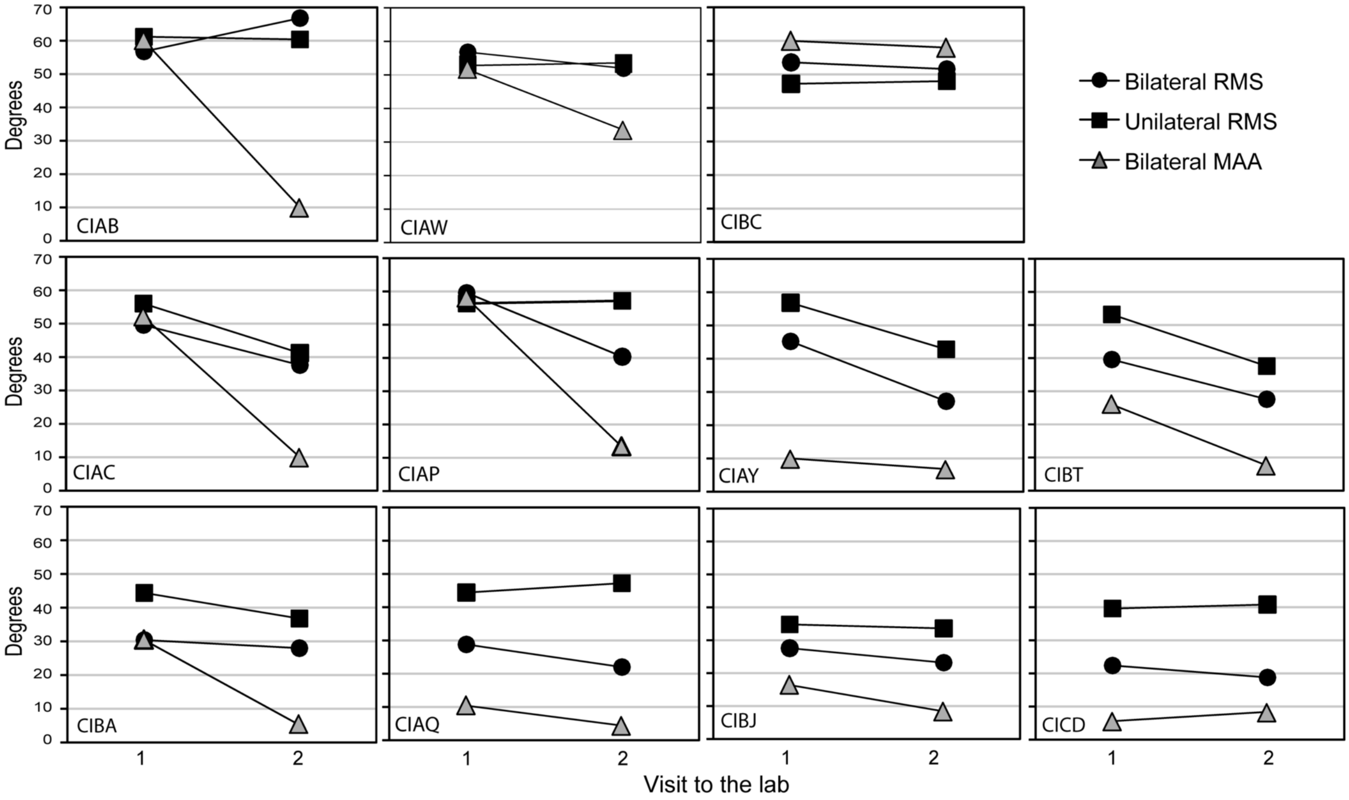

Figure 5.

Changes in sound localization abilities in children after 7–21 months of bilateral experience. RMS errors under the bilateral listening condition (*circles*) and the unilateral listening condition with the first CI (*squares*), as well as minimum audible angle (MAA) under the bilateral listening condition (*triangles*) are illustrated for 11 children who participated in the task on two sequential visits. Three groups of children emerged: children who had RMS errors of >50° in the bilateral condition at visits 1 and 2 (*top row*), children who had and improvement of10° or more in sound source identification between visits 1 and 2 (*middle row*), and children who RMS errors of ≤30° in the bilateral condition at visits 1 and 2 (*bottom row*).

Table 1

Participant demographics. Cochlear implant devices: Freedom, Nucleus, N22, N24 (Cochlear); Clarion, HiFocus, HiRes (Advanced Bionics); Combi, Pulsar (Med-El Corp.).

Participant	Sex	Age of identification (years;mos)	Etiology	Age at visit (years;mos) (Visit #)	Age of first CI (years;mos)	Unilateral experience (years;mos)	Age of second CI (years;mos)	Duration of BICI (years;mos)		First CI (internal device, processor, ear)	Second CI (internal device, processor, ear)	Experimental procedure for source identification task
								Visit 1	Visit 2			
CIAB	F	0;11	Unknown	12;6 (1) 14;3 (2)	6;0	6;3	12;3	0;3	2;0	N22, ESPrit, R	N24, ESPrit 3G, L	15 loudspeakers 10 repetitions
CIAC	F	1;0	Unknown	8:6 (1) 10;3 (2)	4;7	3;9	8;4	0;2	1;11	N24, ESPrit, R	N24, ESPrit 3G, L	15 loudspeakers 10 repetitions
CIAE	F	0;11	Waardenburg Syndrome	7;9	1;7	4;0	5;7	2;2		N24, ESPrit, R	N24, ESPrit 3G, L	7 loudspeakers 5 repetitions
CIAG	M	birth	Unknown^	5;5	1;9	1;4	3;1	2;4		N24, Sprint, R	N24, Sprint, L	7 loudspeakers 10 repetitions
CIAP	F	1;4	Unknown, progressive^	5;5 (1) 6;3 (2)	3;6	1;8	5;2	0;3	1;1	N24, ESPrit, R	N24, ESPrit 3G, L	7 loudspeakers 10 repetitions
CIAQ	M	1;2	Connexin 26	8;5 (1) 9;2 (2)	4;0	4;2	8;2	0;3	1;0	N24, ESPrit, R	N24, ESPrit 3G, L	15 loudspeakers 10 repetitions
CIAT	M	1;5	CMV, progressive^	7;1	4;10	1;11	6;10	0;3		N24, Sprint, L	N24, Sprint, R	7 loudspeakers 10 repetitions
CIAW	M	0;2	CMV	5;8 (1) 6;6 (2)	1;2	4;3	5;5	0;3	1;1	N24, Sprint*, R	Freedom, Freedom, L	7 loudspeakers 10 repetitions
CIAY	M	3;1	Unknown, progressive^	6;3 (1) 7;4 (2)	5;2	0;10	6;0	0;3	1;4	N24, ESPrit 3G*, R	N24, ESPrit 3G*, L	15 loudspeakers 10 repetitions
CIBA	M	2;0	Connexin 26^	10;6 (1) 11;3 (2)	3;7	6;7	10;2	0;4	1;1	N24, ESPrit 3G, L	Freedom, Freedom, R	15 loudspeakers 10 repetitions
CIBC	F	1;8	Unknown	8;5 (1) 9:7 (2)	2;2	6;0	8;2	0;3	1;5	HiFocus, Clarion S-Series, L	HiRes 90K-HiFocus, Auria, R	7 loudspeakers 10 repetitions
CIBG	M	3;6	Unknown^	9;11	5;0	3;10	8;10	1;1		N24, Freedom, R	Freedom, Freedom, L	15 loudspeakers 10 repetitions
CIBH	M	birth	Mondini Syndrome	8;0	1;4	5;8	7;0	1;0		Combi 40+, Tempo+, L	Pulsar, Tempo+, R	7 loudspeakers 10 repetitions
CIBJ	F	2;3	Unknown, progressive^	11;3 (1) 12;0 (2)	7;4	3;7	10;11	0;4	1;1	CII, Auria, L	HiRes 90K, Auria, R	15 loudspeakers 10 repetitions
CIBK	M	1;5	Connexin 26	8;1	2;1	5;0	7;1	1;0		N24, Freedom, R	Freedom, Freedom, L	15 loudspeakers 10 repetitions

Participant	Sex	Age of identification (years;mos)	Etiology	Age at visit (years;mos) (Visit #)	Age of first CI (years;mos)	Unilateral experience (years;mos)	Age of second CI (years;mos)	Duration of BICI (years;mos)		First CI (internal device, processor, ear)	Second CI (internal device, processor, ear)	Experimental procedure for source identification task
								Visit 1	Visit 2			
CIBM	M	3;0	Unknown, progressive^	9;0	3;9	4;4	8;1	0;11		N24, Freedom, L	Freedom, Freedom, R	15 loudspeakers 10 repetitions
CIBO	F	2;1	Pendred Syndrome, progressive^	6;11	2;10	1;11	3;11	3;0		N24, Freedom, R	N24, Freedom, L	15 loudspeakers 10 repetitions
CIBP	F	0;9	Connexin 26	7;10	1;8	5;11	7;7	0;3		HiFocus, PSP, R	HiRes 90K-HiFocus, Auria, L	7 loudspeakers 10 repetitions
CIBQ	M	0;7	Unknown	6;9	1;1	4;5	5;6	1;3		N24, Sprint, R	Freedom, Freedom, L	7 loudspeakers 10 repetitions
CIBT	M	1;2	Unknown	4;11 (1) 5:8 (2)	2;3	2;4	4;7	0;4	1;1	N24, ESPrit 3G*, R	Freedom, Freedom, L	15 loudspeakers 10 repetitions
CICD	M	4;0	Mitochondrial Disorder Complex III, progressive^	13;9 (1) 14;7 (2)	11;0	2;0	13;0	0;9	1;7	N24, Freedom, R	Freedom, Freedom, L	15 loudspeakers 10 repetitions

Asterisks (*) represent children who transitioned to the Freedom processor between visits 1 and 2.

Carets (^) represent children who have a history of acoustic experience.

Table 2

Quantification of performance within each hemifield on the sound source identification task for the BICI group. Shaded gray cells represent significant correlations at $p<0.01$.

Participant	Bilateral RMS (degrees)	LEFT HEMIFIELD			RIGHT HEMIFIELD		
		Responses in correct hemifield	RMS (degrees)	Target-Response Correlation	Responses in correct hemifield	RMS (degrees)	Target-Response Correlation
Group A							
CICD	19.1	100%	21.8	0.78	91%	25.7	0.47
CIAQ	21.9	94%	22.1	0.51	87%	23.7	0.64
CIBJ	23.1	90%	27.3	0.30	89%	17.1	0.84
CIAY	27.4	96%	24.3	0.65	99%	30.0	0.52
CIBT	27.5	90%	27.3	0.48	80%	26.5	0.65
CIBA	27.9	86%	30.8	0.60	99%	26.6	0.50
Group B							
CIBG	32.8	99%	28.9	0.48	69%	36.5	0.39
CIBK	34.7	86%	34.9	0.52	87%	34.3	0.18
CIBO	36.7	81%	36.0	0.35	70%	37.3	.28*
CIAC	37.7	83%	40.9	0.58	91%	36.6	0.33
CIBM	38.9	89%	38.5	0.14	86%	50.6	0.68
CIAE	39.8	80%	38.8	0.24	73%	41.7	.45*
CIAP	40.4	70%	43.4	0.56	87%	40.8	0.19
CIAW	42.5	73%	43.1	−0.14	80%	43.8	0.53
Group C							
CIBP	43.5	87%	34.2	0.27	47%	50.7	0.30
CIBQ	44.1	87%	36.6	−0.05	60%	49.8	.33*
CIBH	48.9	43%	40.5	0.10	27%	53.6	0.16
CIBC	51.8	63%	41.8	0.21	30%	58.4	0.04
CIAT	53.9	53%	54.8	0.06	37%	48.2	0.08
CIAG	56.4	37%	53.9	0.14	33%	55.2	−0.07
CIAB	66.8	36%	70.6	−0.08	51%	61.0	−0.01

Participant	**Bilateral RMS (degrees)**	**LEFT HEMIFIELD**			**RIGHT HEMIFIELD**		
		Responses in correct hemifield	**RMS (degrees)**	**Target-Response Correlation**	**Responses in correct hemifield**	**RMS (degrees)**	**Target-Response Correlation**
NH mean ± SD	*18.3 ± 6.9*	*92.4% ± 5.4%*	*15.6 ± 5.4*	*0.81 ± 0.1*	*89% ± 7.6%*	*20.0 ± 9.4*	*0.72 ± 0.18*

Asterisks (*) represent significant correlations at $p<0.05$. Chance performance: RMS error of 61.1° (15-AFC task) or 56.6° (7-AFC task); Percentage of correct responses in each hemifield of 50%;

Table 3

Coefficients of the multivariate regression analysis with bilateral RMS error as the dependent variable.

Variable	Coefficient	Standard Error	t	Significance
Duration of unilateral implant use	0.278	0.15	1.861	0.84
Duration of bilateral implant use	−0.232	0.341	−0.155	0.508
Age of second implant activation	−0.325	0.095	−3.401	0.004
History of acoustic hearing	7.584	6.003	1.263	0.227