

Sound Localization Skills in Children Who Use Bilateral Cochlear Implants and in Children With Normal Acoustic Hearing

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Objectives: To measure sound source localization in children who have sequential bilateral cochlear implants (BICIs); to determine whether localization accuracy correlates with performance on a right-left discrimination task (i.e., spatial acuity); to determine whether 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; and to determine whether 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 to 14 years) and a group of 7 typically developing children with normal acoustic hearing (5 years). 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 whether 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 multiloudspeaker 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 to 56°. Performance of the normal hearing group, with RMS errors ranging from 9 to 29° was significantly better. Within the BICI group, in 11 of 21 children, RMS errors were smaller in the bilateral versus 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 minimum audible angles. 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.

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.

(*Ear & Hearing* 2010;31:645–656)

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 cochlear implants (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 & Tyler 2003; Litovsky et al. 2004; Nopp et al. 2004; Litovsky et al. 2006c; Neuman et al. 2007; Litovsky et al. 2009; 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 one or more years of experience with the first implant (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. Because 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, b) 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 (MAA), which is the smallest angle that can be discriminated on a left versus right discrimination task (Mills 1958). In the studies by Litovsky et al., 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

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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 ($\pm 90^\circ$ or $\pm 30^\circ$) was better when BICIs were used than when a unilateral CI was used (Beijen et al. 2007; Galvin et al. 2008; Steffens et al. 2008). In addition, similarly aged children with bimodal fittings (i.e., CIHA) 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 $\pm 70^\circ$. Performance was quantified with a standard method of calculating root mean square (RMS) error, which is computed from the trial-by-trial deviations of the judged location to the actual source location. To determine whether 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 laboratory for a second round of testing at least 7 months after the first testing protocol was completed.

MATERIALS AND METHODS

Subjects

Children With BICIs • Twenty-one children between 5 and 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 after 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) before deafness and implantation. Children were free from other medical complications. Despite active recruitment of participants with all three CI 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 to 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 CLXX, 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 laboratory.

Because of the limited number of young children with sequential BICIs 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, because 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 2 days working in the laboratory during which time 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, b). In addition, 11 of the 21 children participated in the research program at two sequential visits after the activation of their second CI.

Children With Normal Acoustic Hearing • Seven 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) because 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 Setup

Testing was conducted in a sound-treated booth (IAC, reverberation time of 250 msec) 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 section). Each loudspeaker was assigned a child-friendly visual icon that served as that loudspeakers' reference during the task (see Procedure section). Hardware included a Tucker-Davis System III (Tucker-Davis Technologies, Alachua, FL) with a multiplexer for loudspeaker selection and a PC host. Customized software for

TABLE 1. Participant demographics

Participant	Sex	Age of identification (yr;mo)	Etiology	Age at visit (yr;mo) (Visit #)	Age of first CI (yr;mo)	Unilateral experience (yr;mo)	Age of second CI (yr;mo)	Duration of BCI (yr;mo)		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	ClI, 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
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

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

* Children who transitioned to the Freedom processor between visits 1 and 2.

† Children who have a history of acoustic experience.

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., three bursts of 25 msec pink noise with 5 msec rise/fall times and 250 msec interstimulus interval; Litovsky et al. 2004). After testing a few children with this stimulus (including CIAB and CIAC who are reported in this study), 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 and 64 dB SPL (roved by ± 4 dB) from trial to trial 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 (Nopp et al. 2004; van Hoesel 2004; Litovsky et al. 2006, 2009) and to maintain stimulation levels within the meaningful dynamic range of CI 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 seems to maintain interaural 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 before 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 2-AFC task was completed before 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 $\pm 70^\circ$ to $\pm 10^\circ$). Children who had ceiling effects at $\pm 10^\circ$ repeated the task with speakers at $\pm 2.5^\circ$ and $\pm 5^\circ$. 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 $\geq 75\%$ 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 (Litovsky & Macmillan 1994; Litovsky 1997). 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 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, b).

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-AFC or 15-AFC 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 ($\pm 10^\circ$, $\pm 30^\circ$, $\pm 50^\circ$, and $\pm 70^\circ$) 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 $< 30^\circ$ (an angle deviation that is two 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 to 150 trials per child, with the exception of one child: CIAE completed only five trials per loudspeaker because of fatigue. All children in the NH group participated in a 15-AFC task. The RMS error between the azimuth of the stimulus location and the listener's response was used to quantify localization accuracy. Chance performance ± 1 SE unit was calculated to be $61.1 \pm 3.6^\circ$ for the 15-AFC task and $56.6 \pm 4.6^\circ$ for the 7-AFC task (Hartmann et al. 1998).

Data from this task were 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

TABLE 2. Quantification of performance within each hemifield on the sound source identification task for the BICI group

Participant	Bilateral RMS (°)	Left hemifield			Right hemifield		
		Responses in correct hemifield (%)	RMS (°)	Target-Response correlation	Responses in correct hemifield (%)	RMS (°)	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	0.28*
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	0.45*
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	0.33*
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
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

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%.

* Significant correlations at $p < 0.05$. Shaded gray cells represent significant correlations at $p < 0.01$.

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, 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 2A, respectively. All children had RMS errors that were $<30^\circ$ (range: 8.9 to 29.2°).

In contrast to the NH group, there was a larger range of RMS errors (19 to 56°) among children who use BICIs in the bilateral condition under similar experimental settings (Figs. 1B and 2B). Visual inspection of the individual scatter plots

(Fig. 1B) revealed large variability in sound source identification skills within the BICI group. Despite the variability, all but three children (CIAT, CIAG, and 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%; 2 SDs 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 2 SDs of the NH group average (left: 92% \pm 5.4%, right: 89% \pm 7.6%, mean \pm 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 2 SDs of the NH group average (18.3 \pm 6.9°, $N = 7$). Group B included eight 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 correlations between the targets and responses. Their bilateral RMS errors ranged from 32.8 to 42.5°, which were larger by more than 2 SDs of the NH group average.

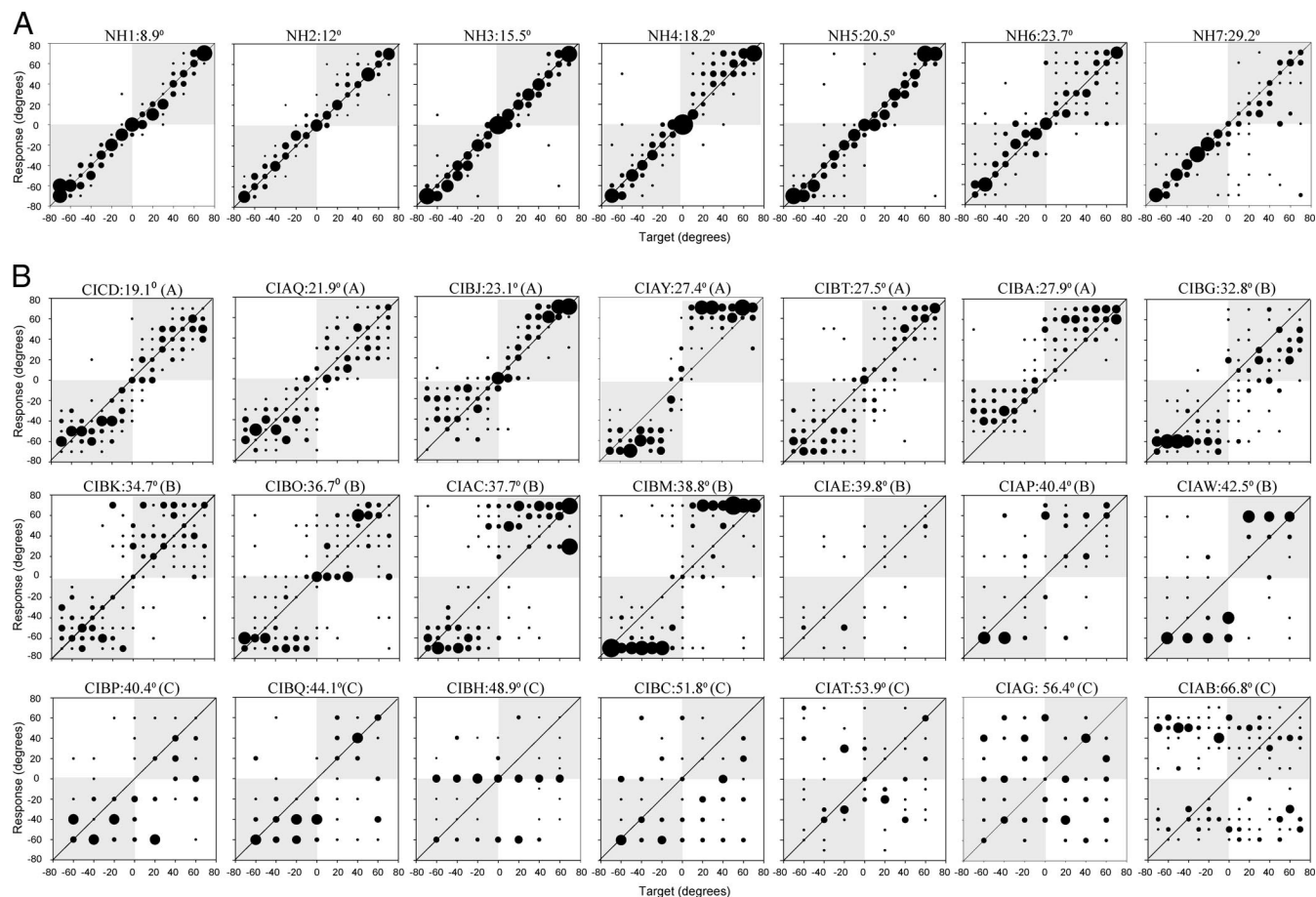


Fig. 1. Individual performance on the sound source identification task in the normal hearing (NH) group (A) and the bilateral cochlear implant (BICI) group (B). The size of the dots represents the number of responses for a given target location. Larger dots reflect a greater number of responses. The diagonal line represents perfect performance. Letters in the parentheses indicate the subgroup that each child in the BICI group belongs to based on performance.

Finally, group C included seven 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 three children and in both hemifields for four 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 because they localized a different auditory stimulus than the NH group (see Methods, Stimuli). On average, the BICI group had significantly poorer localization accuracy ($37.4 \pm 11.0^\circ$, $N = 19$) than the NH group ($18.3 \pm 6.9^\circ$, $t[24] = 4.2$, $p < 0.001$). Although RMS error is a good tool for condensing performance down to a single metric, it is clearly not reflective of the

Fig. 2. Individual performance on the sound source identification task (as quantified by root mean square [RMS] error) for the normal hearing (NH) group (A) and the bilateral cochlear implant (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 alternative forced-choice (7-AFC) task and the dashed line represents chance performance for the 15-AFC task.

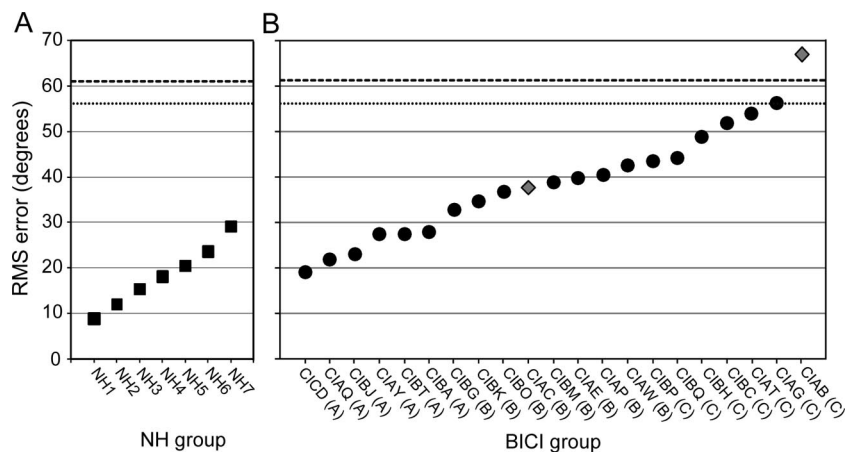


TABLE 3. Coefficients of the multivariate regression analysis with bilateral RMS error as the dependent variable

Variable	Coefficient	SE	<i>t</i>	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

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, Fig. 1A). Although 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 (Fig. 1B, top row) 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. 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.

Relation 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 MAA) typically emerge within 12 or more months after activation of the second implant in children who have sequential BICIs (Litovsky et al. 2006a, b). 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

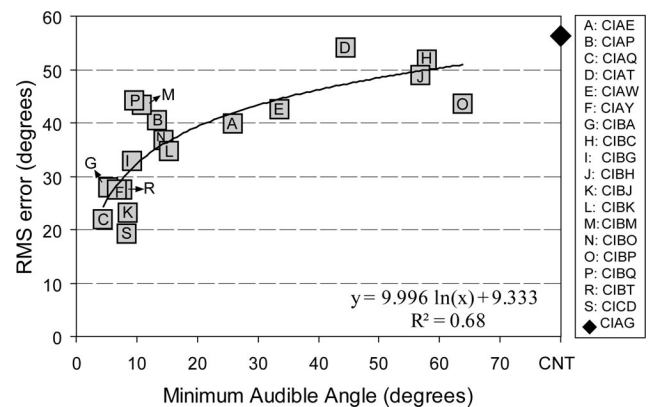


Fig. 3. Relationship between sound localization accuracy (as quantified by root mean square [RMS] error) and spatial acuity (as quantified by minimum audible angle). CNT: Minimum audible angle (MAA) could not be calculated because CIAG did not perform at above chance levels on the maximum angle separation ($\pm 70^\circ$).

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 to 44.1°) for children who had relatively small MAAs ($< 20^\circ$). 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 whether 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 (Figs. 2B and 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 ($45.6 \pm 7.1^\circ, N = 19$) to also be significantly poorer than the RMS errors reported above for the NH group ($8.3 \pm 6.9^\circ, N = 7, t[24] = 8.7, p < 0.001$).

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

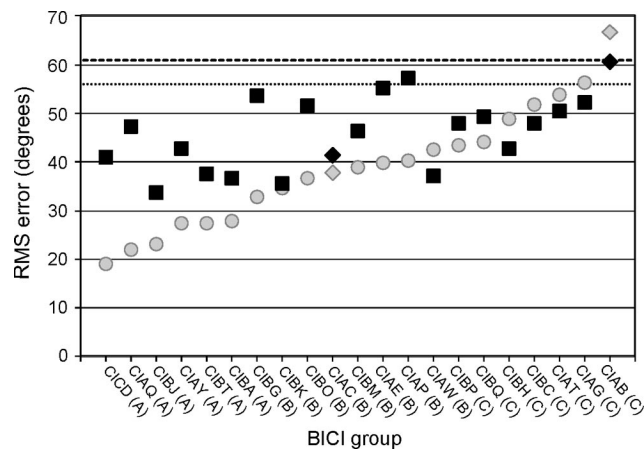


Fig. 4. Individual performance of the bilateral cochlear implant (BICI) group on the sound source identification task (as quantified by root mean square [RMS] error) when using a single cochlear implant (squares). Data from the bilateral condition (circles, from Fig. 2B) are plotted for comparison. Data 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 alternative forced-choice (7-AFC) task and the dashed line represents chance performance for the 15-AFC task.

2 SE 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 11 of the children exhibited significantly better performance when using both CIs compared with the single-CI condition; 10 children did not perform significantly different in the two listening conditions. A multivariate linear regression analysis was completed in an 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 ($F[4,14] = 1.04$, $p = 0.42$).

Emergence of Spatial Hearing Abilities Over Time

To determine whether sound localization abilities mature with increasing bilateral experience, 11 children were retested 7 to 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 the 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., $>50^\circ$) at both visits

(top row), (2) children who showed a reduction of RMS errors (i.e., improvement) by $\geq 10^\circ$ between visits 1 and 2 (middle row), and (3) children who had relatively small RMS errors (e.g., $\leq 30^\circ$) 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 ($N = 3$; Fig. 5, top row) tended to have large RMS errors with their first CI alone on both visits as well. However, two of the three children showed an improvement in bilateral MAA. Children who had improvements of 10° or more (i.e., >2 SE units) in localization accuracy with their BICIs on visit 2 had similar improvements in spatial acuity ($N = 4$; Fig. 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 and 30° on visit 1 ($N = 4$; Fig. 5, bottom row) had small reductions in RMS errors on visit 2. Three of the four children had a concomitant improvement in bilateral MAA. Changes in performance were not observed, however, for three of the four children when they used their first CI alone.

DISCUSSION

This is one among the first studies to measure sound source localization accuracy using a large array of loudspeakers in children who use sequential BICIs. Of the 21 children in this study, 10 had RMS errors of $\leq 40^\circ$ 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 laboratory (Litovsky et al. 2006a, b; Godar & Litovsky¹) as well as others (Beijen et al. 2007; Galvin et al. 2008). However, it is important to note that a control group that 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 NH. The results from this study were in slight conflict with data from a recent study by Van Deun et al. (2009). In the study by Van Deun et al. (2009), 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 this study ($18.3 \pm 2.6^\circ$). 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 this study, the stimulus was speech ("base-

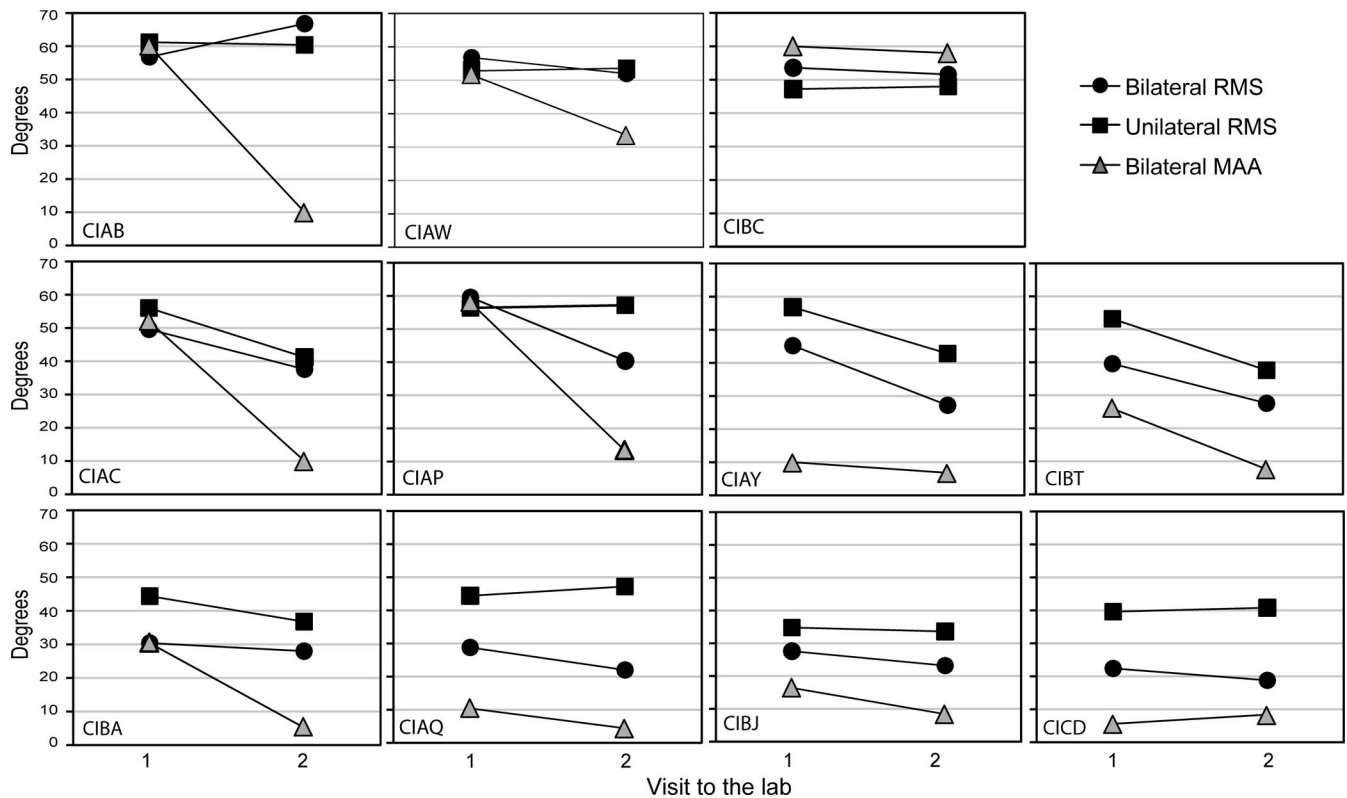


Fig. 5. Changes in sound localization abilities in children after 7 to 21 months of bilateral experience. Root mean square (RMS) errors under the bilateral listening condition (circles) and the unilateral listening condition with the first cochlear implant (squares) as well as minimum audible angle (MAA) 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 $>50^\circ$ in the bilateral condition at visits 1 and 2 (top row), children who had and improvement of 10° or more in sound source identification between visits 1 and 2 (middle row), and children who RMS errors of $\leq 30^\circ$ in the bilateral condition at visits 1 and 2 (bottom row).

ball”) 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 this study. The task in this study was most likely more challenging, and the stimuli were more difficult to localize compared to those in the study by Van Deun et al., resulting in overall poorer performance and 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 (Kirk et al. 2002; Nicholas & Geers 2006; Wang et al. 2008) 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 before activation of their second CI. The results of this 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, and CIBJ) seem 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, and 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 the children’s lack of understanding of the task, because substantial training and feedback were provided before 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, because of 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 were 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. However, the observation that the children in the BICI group with the smallest RMS errors had some acoustic hearing before 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 after implantation. Nicholas and Geers (2006) found a similar benefit of early acoustic experience on language outcomes in children who use CIs. Further studies are needed to investigate this issue.

Relation 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 to 5°, depending on the stimulus and exact task (Mills 1958; Litovsky & Macmillan 1994). 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 multisource 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. On the other hand, localization RMS errors represent a measure of the deviation of response from the target position. Although the same azimuthal-related decision axis is involved, the decision is based on a more complex decision variable than selection between two distributions.

These 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 & Rakerd 1989; Recanzone et al. 1998; Moore et al. 2008). Together with other findings using identical methods (Litovsky et al. 2006a; Godar & Litovsky¹), there is evidence to suggest that although 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 to 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. However, longitudinal data over a number of visits from additional children are needed before any conclusions can be drawn from these data.

Prolonged Unilateral Experience

A number of children in this study experienced stimulation with a unilateral CI for a prolonged period of time before the activation of their second implant. Overall, there was a large range of unilateral CI experience (10 to 142 months). Although long periods of unilateral stimulation can disrupt binaural brain stem processing as measured with electric auditory brain stem response (Gordon et al. 2008), there is no evidence of disruption of localization accuracy in this study because 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 electric auditory brain stem response 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. 2007). 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 (Litovsky et al. 2009). Taken together, it seems that experience has a role in the establishment of sound localization abilities in CI users.

The acoustic cues that would be used under unilateral listening conditions are most likely overall level cues. In this 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 used by, a number of the children.

Potential Limitations of BICIs

Although postlingually deafened adults and prelingually deafened children seem 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 Blauert 1997; Bernstein 2001). Because 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 (van Hoesel 2004; Grantham et al. 2007; Seeber & Fastl 2008).

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 nonimplanted 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 because 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.

ACKNOWLEDGMENTS

The authors thank the children and their families for their time and dedication to this study as well as the following clinics: Arkansas Children's Hospital, Beth Israel/New York Eye & Ear Cochlear Implant Center, Carle Clinic Association (IL), Children's Hospital Boston, Children's Memorial Hospital Chicago, Cincinnati Children's Hospital, Cleveland Clinic, Dallas Otolaryngology Associates, Jones Institute for Rehabilitative Audiology, NYU Cochlear Implant Center, Riley Hospital for Children (IN), and University of Iowa. The authors also thank Gongqiang Yu for software development and troubleshooting; Daniel Bolt for assistance with statistical analyses; Shelly Godar and Patti Johnstone for help in data collection; and numerous undergraduate students who assisted during data collection.

This work was supported by NIH NIDCD grant numbers R21DC006642 and 5R01DC8365 (to R.Y.L.) and F32DC008452 (to T.M.G.-C.).

R.Y.L. has consulted and provided written materials for distribution for Cochlear Americas.

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Received April 27, 2009; accepted April 23, 2010.

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