Spatial Acuity in 2-to-3-Year-Old Children With Normal Acoustic Hearing, Unilateral Cochlear Implants, and Bilateral Cochlear Implants

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Objectives: To measure spatial acuity on a right–left discrimination task in 2-to-3-year-old children who use a unilateral cochlear implant (UCI) or bilateral cochlear implants (BICIs); to test the hypothesis that BICI users perform significantly better when they use two CIs than when using a single CI, and that they perform better than the children in the UCI group; to determine how well children with CIs perform compared with children who have normal acoustic hearing (NH); to determine the effect of intensity roving on spatial acuity.

Design: Three groups of children between 26 and 36 months of age participated in this study: 8 children with NH (mean age: 30.9 months), 12 children who use a UCI (mean age: 31.9 months), and 27 children who use BICIs (mean age: 30.7 months). Testing was conducted in a large sound-treated booth with loudspeakers positioned in a horizontal arc with a radius of 1.2 m. The observer-based psychophysical procedure was used to measure the children's ability to identify the hemifield containing the sound source (right versus left). Two methods were used for quantifying spatial acuity, an adaptive-tracking method and a fixed-angle method. In Experiment 1 an adaptive tracking algorithm was used to vary source angle, and the minimum audible angle (MAA), the smallest angle at which right–left discrimination performance is better than chance, was estimated. All three groups participated in Experiment 1. In Experiment 2 source angles were fixed at ±50 degrees, and performance was evaluated by computing the number of SDs above chance. Children in the UCI and BICI groups participated in Experiment 2.

Results: In Experiment 1, when stimulus intensity was roved by 8 dB, MAA thresholds were 3.3 degrees to 30.2 degrees (mean = 14.5 degrees) and 5.7 degrees to 69.6 degrees (mean = 30.9 degrees) in the NH group and in the BICI group, respectively. When the intensity level was fixed for the BICI group, performance did not improve. Within the BICI group, 5 out of 27 children obtained MAA thresholds within one SD of their peers who have NH; all five had >12 months of bilateral listening experience. In Experiment 2, BICIs provided some advantages when the intensity level was fixed. First, the BICI group outperformed the UCI group. Second, children in the BICI group who repeated the task with their 1st CI alone had statistically significantly better performance when using both devices. In addition, when intensity roving was introduced, a larger percentage of children who had 12 or more months of BICI experience continued to perform above chance than children who had <12 months of BICI experience. Taken together, the results suggest that children with BICIs have spatial acuity that is better than when using their first CI alone and than that of their peers who use UCIs. In addition, longer durations of BICI use tend to result in better performance, although this cannot be generalized to all participants.

Conclusion: This report is consistent with a growing body of evidence that spatial-hearing skills can emerge in young children who use BICIs. The observation that these skills are not concomitantly emerging in age- and experience-matched children who use UCIs suggests that BICIs provide cues that are necessary for these spatial-hearing skills that UCIs do not provide.

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INTRODUCTION

There is increasing evidence that bilateral cochlear implants (BICIs) can provide benefits to individuals who are deaf. Although there seems to be widespread variability among recipients in the extent of the benefit, research has shown that, overall, both adults and older children exhibit better performance when using BICIs versus a single implant in studies of either speech understanding in noise (e.g., Litovsky et al. 2006c; Mok et al. 2010), sound localization (e.g., Nopp et al. 2004; Litovsky et al. 2006a; Neuman et al. 2007; Godar & Litovsky 2010; Grieco-Calub & Litovsky 2010), or in studies that evaluated both skill sets (e.g., Tyler et al. 2002; van Hoesel & Tyler 2003; Litovsky et al. 2006b; Litovsky et al. 2009). It also seems that, compared with children who have exposure to unilateral input for longer periods of time, children who are provided with BICIs earlier in life have more mature neural representation at the level of the brainstem for binaural stimuli (Gordon et al. 2007).

In the unilateral research domain, there is evidence showing that better language outcomes and more mature auditory neurophysiology are often associated with earlier ages of implantation (e.g., Kirk et al. 2002; Sharma et al. 2005; Nicholas & Geers 2006; Wang et al. 2008). These outcomes are most likely because early implantation reduces the duration of auditory deprivation and allows stimulation of the auditory system during a time of great neural plasticity. Based on this notion, it might be argued that providing infants with BICIs should result in greater bilateral benefits. To date, however, little is known about whether providing BICIs to young children results in better functional outcomes. Furthermore, it is not clear whether there are benefits to providing the second CI simultaneously with (or near the time of) the first device versus sequentially (month or year apart).

This uncertainty is in part driven by the unknown extent to which young CI users can access the auditory cues necessary to drive the development of spatial hearing. This is largely because of the fact that bilateral CIs have independent inputs, and because the lack of coordination between the two devices renders binaural cues weak, absent, or inconsistent. Previous work has shown that children with sequential BICIs are capable of developing spatial-hearing skills that are equivalent to that of their peers who have normal acoustic hearing (NH), but there is large individual variability in outcomes (Grieco-Calub & Litovsky 2010). There is an open question as to whether providing BICIs at very young ages, with little to no delay between the activation of the two devices, can reduce this variability and improve spatial-hearing outcomes for young BICI users. This question will be addressed in the present study. The success of BICIs in postlingually deafened adults and older children has prompted an increase in the number of infants who are provided with

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BICIs; thus the present study, which examined spatial-hearing skills in 2-to-3-year-old children with BICIs, became feasible.

Infants with normal hearing are born with the rudimentary ability to discriminate between sources presented from the right versus left of midline. Although rather immature, this spatial acuity is present at birth (Muir & Field 1979) and improves with an increase in age. For example, the minimum audible angle (MAA; Mills 1958), the smallest angle at which right–left discrimination performance is better than chance, decreases throughout childhood. With simple stimuli such as brief noise bursts, children exhibit adult-like performance by 5 years of age (Litovsky 1997; for review, see Litovsky & Ashmead 1997; Litovsky 2011). However, under more complex conditions, such as when simulated echoes occur, children's spatial acuity is worse than that of adults (Litovsky 1997).

On measures of sound-location identification using an array of loudspeakers in the horizontal plane, children as young as 4–5 years of age exhibit relatively low error rates, averaging between 10 degrees and 20 degrees root mean square error (Grieco-Calub & Litovsky 2010; Litovsky & Godar 2010). Again, when simulated echoes are introduced, children's performance is significantly worse than that of adults (Litovsky & Godar 2010), suggesting that spatial-hearing abilities continue to mature during later childhood. The factors that are responsible for these developmental changes are poorly understood.

The auditory experience of young children who are born deaf and who subsequently receive BICIs is quite unique relative to that of their peers who have normal acoustic hearing. Depending on the etiology and cause of deafness, these children experience severe or complete auditory deprivation before, beginning at, or shortly after birth, until they receive their first CI. In cases of sequential implantation, children function as unilateral CI (UCI) users until they receive their second implant. Research to date shows that most children with BICIs have significantly poorer spatial-hearing skills than their peers with normal hearing. These children perform significantly better, however, when using both CIs than when a single CI is used. There are bilateral benefits when children are tested on discrimination of sound sources presented to the right versus left hemifields in the frontal horizontal plane (i.e., smaller MAAs; Litovsky et al. 2006a; Grieco-Calub et al. 2008). There is also evidence for bilateral benefits on measures of source-location identification (i.e., smaller root mean square errors; Grieco-Calub & Litovsky 2010) and speech intelligibility (Litovsky et al. 2006b; Mok et al. 2010).

The children tested to date on right–left discrimination and sound-location identification tasks varied in the age at which they received their second implant as well as the amount of time between activation of the first and second implants (e.g., Litovsky et al. 2006a; Godar & Litovsky 2010; Grieco-Calub & Litovsky 2010; Van Deun et al. 2010). Until recently, reports included children who received their first CI at slightly older ages than the children in the present study and who had a number of years of unilateral auditory deprivation before the activation of their second implant. Some children in this group were successful users of a hearing aid (HA) in the contralateral, nonimplanted ear before receiving the second implant (i.e., bimodal users, CI+HA). The extent to which preimplant auditory stimulation in the second ear aids in post-BICI performance is unknown. Studies involving children who are CI+HA users have shown varied outcomes on speech-in-noise and spatial-hearing tasks. There is evidence to suggest that bilateral input, regardless of the mode (BICI or CI+HA) can aid in speech perception; however, performance with the second device alone (second CI or HA) is typically better in the BICI users (Mok et al. 2010). There is also evidence, however, suggesting that the addition of a HA can, in some children, impair speech perception relative to using the first CI alone (Litovsky et al. 2006b). Regarding spatial hearing, in a between-subjects design, Litovsky et al. (2006b) found that MAA thresholds were lower (i.e., performance was better) in children who use BICIs compared with children who use CI+HA. In a within-subjects design, Godar and Litovsky (2010) tested 10 children who used a single CI with either no other device (UniCI) or a HA (CI+HA) in the opposite ear before implantation of a second CI. Upon retesting the children at 3 and 12 months after bilateral activation, the authors reported significant improvement in the MAA threshold in the group overall; however, intersubject variability was high. Children who had bilateral input (CI+HA) before activation of their CI did not outperform children who only used their first CI before activation of their second CI. Possible reasons for this variability most likely relates to individual factors such as the amount of residual hearing and etiology of the hearing loss in these children.

Periods of bilateral, followed by unilateral, auditory deprivation (whether partial or complete) may have rendered spatial-hearing mechanisms that are not ideally wired for processing spatial cues with fidelity in these children. In fact, research with nonhuman species has provided some support for this suggestion. For example, bilaterally implanted cats that experienced long durations of auditory deprivation (from birth) had poorer sensitivity to interaural cues than cats that were deafened after having some experience with sound both within the inferior colliculus (Hancock et al. 2010) as well as in the auditory cortex (Tillein et al. 2010). In addition, unilateral deprivation (in the form of a conductive block) during development disrupted binaural integration of interaural level differences (ILDs) in the auditory cortex of the rat (Popescu & Polley 2010). Taken together, long periods of bilateral or unilateral deprivation may preclude the development of spatial-hearing skills even when BICIs are provided.

There is a growing population of children who received their first implant by 1 year of age and who have little to no duration between activation of the first and second implants, consistent with the clinical trends of providing BICIs to infants. With this growing trend, the duration of auditory deprivation has been decreased, and the amount of unilateral experience before bilateral activation is generally shorter. This study was motivated by the question of whether bilateral stimulation, provided at a time of great neural plasticity, can promote normal or near-normal spatial-hearing skills in young implant users. The underlying hypothesis in the present project is that providing BICIs at young ages will improve performance in a spatial-hearing task where individuals typically benefit from access to bilateral information.

In an earlier report where preliminary results from this study were presented, the observer-based psychophysical procedure was used to determine whether 2-to-3-year-old children who receive BICIs before or near 2 years of age perform more similarly to their peers than children who gain access to bilateral hearing at older ages (Grieco-Calub et al. 2008). Results from that preliminary study indicated that early bilateral implantation has mixed results. Only half of the children who used BICIs were able to identify the location of the sound source on a right–left discrimination task in the study at a level that was above-chance performance. As a result, discussion about the emergence of spatial-hearing skills in these young children was limited because performance could not be quantified for all children.

The present study extends the preliminary findings to 39 implanted children between 26 and 36 months of age: 27 were BICI users and 12 were UCI users. The primary goal of the present study was to estimate spatial-hearing acuity in these young CI users. Like in Grieco-Calub et al. (2008), children were asked to identify the hemifield containing the sound source on two different versions of a 2-alternative-forced choice right–left task. For the adaptive-tracking method, during which the source angle varied, spatial hearing was quantified by MAA thresholds. For the fixed-angle method, during which the source angle was fixed at ±50 degrees, spatial hearing was quantified by the number of SDs above chance. The rationale for using these two methods is discussed later. The other goals of this study were to determine if there is a functional difference in performance between the BICI and UCI groups, and to determine the effect of intensity roving, whereby monaural level cues are minimized, on spatial acuity.

MATERIALS AND METHODS

Subjects

Children With Cochlear Implants (CIs) • Participants were 39 children between 26 and 36 (mean = 31.1) months of age who use CIs. All children had a history of severe-to-profound bilateral sensorineural hearing loss, either identified at birth (N = 35) or after some experience with acoustic hearing (N = 4) as per parental report (Table 1). At the time of participation, 12 children were UCI users and 27 children were BICI users. The children were recruited from across the United States through their audiologists, surgeons, or self-referrals, and traveled to Madison, WI, to participate in the experiments. 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. In addition, every effort was made to recruit equal numbers of children who use CIs from the three implant manufacturers: Advanced Bionics (16 children), Cochlear Corporation (16 children), and Med-El Corporation (7 children).

Children spent 2 days being tested in the laboratory, during which time they participated in tasks designed to quantify spatial hearing and spoken-word recognition. Participant codes are in the format CI*XX*, representing the order in which they enrolled in the research program. Results from 18 of the children who participated in this study have been cited in a preliminary report on spatial-hearing acuity (Grieco-Calub et al. 2008). Results from 26 of the children have been cited in a previous report that focuses on their spoken-word recognition abilities (Grieco-Calub et al. 2009).

Children With Normal Hearing (NH) • Eight children who were typically-developing and 26 to 36 (mean = 30.9) months of age participated in the study. These children had no history of hearing loss, middle ear problems, or other developmental delays as per parental report.

Experimental Setup

All measures were conducted in a double-walled sound-treated booth (IAC; 2.8 m × 3.25 m with reverberation time [RT_{60}] of 250 msec). Fifteen loudspeakers that were visible to the children were mounted on a custom-made arc spanning 140 degrees and positioned at 10-degree intervals. The loudspeakers were digitally matched; any subtle differences in frequency response were digitally subtracted before stimulus presentation. The purpose of this technique is to ensure consistent spectral representation of the stimuli across speakers. For children in the NH group, and for five children in the BICI group (see Procedure), the 15 loudspeakers were placed between ±50 degrees (spanning 100 degrees) at the following intervals: 0 degrees, ±2.5 degrees, ±5 degrees, ±10 degrees, ±20 degrees, ±30 degrees, ±40 degrees , and ±50 degrees. The rationale for repositioning the loudspeakers was to obtain a more precise estimate of the children's spatial acuity. Two computer monitors, mounted underneath the loudspeakers located at 45 degrees to the right and left of midline, were used to provide feedback and reinforcement via video presentation. A camera, placed at 0 degrees underneath the center loudspeaker, provided video feed into the observation side of the test booth, which was used by an observer to monitor the children's behavior. Children sat either on their caregivers' lap or alone on a chair, always in the center of the loudspeaker array, with the head at an approximate distance of 1.2 m from the loudspeakers. Caregivers and research assistants in the test booth used earphones that provided a diotic presentation of the stimulus on each trial, to mask the source locations, thereby eliminating tester bias and potential for input from caregivers during the experiment. Auditory stimuli were stored as wav files on a PC host, and played to the loudspeakers via Tucker-Davis System III hardware (Tucker-Davis Technologies, Alachua, FL). Customized software for stimulus presentation and data collection was written in MATLAB programming language.

Stimuli

Stimuli were the spondaic words "baseball" and "birthday," recorded with a male voice at a sampling rate of 44 kHz and stored as .wav files. On each trial, one word was randomly chosen and repeated three times (e.g., "baseball, baseball, baseball"). In some conditions, stimuli were presented at an intensity level that was fixed at 60 dB SPL (i.e., fixed-intensity level conditions). When the intensity is fixed, the listener may have the opportunity to access both interaural-difference cues and monaural-intensity cues. Monaural-intensity cues vary in each ear as sound-source angles are varied (Shaw 1974; Blauert 1997); therefore, when these cues are available, they might be used to locate the sound-source location. The extent to which CIs preserve these cues is still an empirical question.

In the remaining conditions, stimuli were presented at varying intensity levels. In these intensity-rove conditions, the stimulus level was randomly varied over an 8 dB range (60 ± 4 dB SPL) across trials to minimize the availability of monaural-level cues that are present when sound intensity is fixed. The level rove was selected to maintain stimulation levels within the meaningful dynamic range of CI processors, where compression is minimal or absent. This degree of rove is also consistent with prior studies in this lab (Litovsky et al. 2006a, 2009; Grieco-Calub & Litovsky 2010) and others (Galvin et al. 2008).

TABLE 1. Demographic information

Participant	Sex	Age of ID (yrs;mos)	Etiology	Age at Visit (mos)	Age at First CI (mos)	Hearing Age (mos)	Age at Second CI (mos)	Duration of BICI (mos)	First CI (Internal Device, Processor, and Ear)	First CI Speech Processing Strategy	Second CI (Internal Device, Processor, and Ear)	Second CI Speech Processing Strategy
BICI group												
CIBV	M	Birth	Connexins 26, 30	29	17	12	23.5	5.5	HiRes, PSP, R	HiRes-S	HiRes, PSP, L	HiRes-S
CIBX	M	Birth	Waardenburg Syndrome	31.5	10	21.5	12	19.5	N24, Sprint, R	ACE	N24, Sprint, L	ACE
CICA	M	2;0	Unknown	35	29	6	29	6	Pulsar, Tempo, simultaneous	CIS+	Pulsar, Tempo, simultaneous	CIS+
CICB	F	Birth	Connexin 26	31	10.5	20.5	25	6	N24, Sprint, R	ACE	Freedom, Freedom, L	ACE (RE)
CICF	F	2;0	Meningitis*	34.5	18	16.5	28.5	6	Freedom, Freedom, R	ACE	Freedom, Freedom, L	ACE
CICG	M	Birth	Connexin 26	27	13	14	20.5	6.5	C40+, Tempo, R†	CIS+	Pulsar, Tempo, L†	CIS+
CICH	M	Birth	Unknown	27	12	15	12	15	Pulsar, Tempo, R†	CIS+	Pulsar, Tempo, L†	CIS+
CICK	M	0;11	Connexin 26	28.5	13	15.5	15.5	13	HiRes, PSP, R	HiRes P	HiRes, PSP, L	HiRes-P
CICO	M	Birth	Connexin 26	31	14	17	25.5	5.5	Freedom, Freedom, R	ACE (RE)	Freedom, Freedom, L	ACE (RE)
CICP	F	Birth	Connexin 26	26.5	13	13.5	20	6.5	Freedom, Freedom, R	‡	Freedom, Freedom, L	‡
CICR	M	Birth	Connexin 26	26	12.5	13.5	16.5	9.5	HiRes, PSP, L	HiRes-P w/ Fidelity 120	HiRes, PSP, R	HiRes-P w/ Fidelity 120
CICS	M	0;10	Connexin 26	34.5	18	16.5	18	16.5	HiRes, Harmony, simultaneous	HiRes-P w/ Fidelity 120	HiRes, Harmony, simultaneous	HiRes-P w/ Fidelity 120
CICT	M	Birth	Connexin 26	35	11.5	23.5	22.5	12.5	HiRes, PSP, R	HiRes-P w/ Fidelity 120	HiRes, PSP, L	HiRes-P w/ Fidelity 120
CICU	F	Birth	Unknown*§	31	15	16	24	7	Freedom, Freedom, L	ACE	Freedom, Freedom, R	ACE
CICV	M	Birth	Connexin 26	33.5	12	21.5	26	7.5	HiRes, Harmony, R (T-mic)	HiRes-P w/ Fidelity 120	HiRes, Harmony, L (T-mic)	HiRes-P w/ Fidelity 120
CICW	F	0;1	Unknown	29	14	15	15	14	Pulsar, Tempo, R†	CIS+	Pulsar, Tempo, L†	CIS+
CICX	F	Birth	Unknown	36	20.5	15.5	27.5	8.5	Freedom, Freedom, R	ACE	Freedom, Freedom, L	ACE
CIDA	F	Birth	Connexin 26	34.5	11	23.5	22	12.5	HiRes, PSP, R	HiRes-P w/ Fidelity 120	HiRes, PSP, L	HiRes-P w/ Fidelity 120
CIDC	M	Birth	Unknown*§	31	18	13	18	13	HiRes, Auria, L	HiRes-S	HiRes, PSP, R	HiRes-S
CIDD	F	1;1	Unknown	36	21	15	29	7	Freedom, Freedom, L	ACE	Freedom, Freedom, R	ACE
CIDE	M	Birth	Unknown	26.5	13	13.5	13	13.5	HiRes, PSP, simultaneous	HiRes-P	HiRes, PSP, simultaneous	HiRes-P
CIDH	M	0:10	Unknown	35.5	17	18.5	26	9.5	Freedom, Freedom, R	ACE	Freedom, Freedom, L	ACE

(Continued)

TABLE 1. Continued.

Participant	Sex	Age of ID (yrs;mos)	Etiology	Age at Visit (mos)	Age at First CI (mos)	Hearing Age (mos)	Age at Second CI (mos)	Duration of BICI (mos)	First CI (Internal Device, Processor, and Ear)	First CI Speech Processing Strategy	Second CI (Internal Device, Processor, and Ear)	Second CI Speech Processing Strategy
CIDI	M	Birth	Connexin 26	26	8	18	9	17	Pulsar, Tempo, L†	CIS+	Pulsar, Tempo, R†	CIS+
CIDK	M	Birth	Connexin 26	26.5	9.5	17	9.5	17	Freedom, Freedom, simultaneous	ACE	Freedom, Freedom, simultaneous	ACE
CIDL	F	Birth	Connexin 26	27.5	14	13.5	18	9.5	Pulsar, Tempo, R†	CIS+	Sonata, Tempo, L†	CIS+
CIDM	F	Birth	Unknown	31.5	13	18.5	25	6.5	HiRes, Harmony, L	HiRes-P w/ Fidelity 120	HiRes, Harmony, R	HiRes-P w/ Fidelity 120
CIEA	M	Birth	Connexin 26	28	8	20	11	17	Freedom, Freedom, R	ACE (RE)	Freedom, Freedom, L	ACE (RE)
UCI group												
CICC	M	Birth	Familial (hereditary)	36	15	21			N24, Sprint, L	ACE		
CICE	M	Birth	Connexins 26, 30	30	10.5	19.5			HiRes, Auria, R	HiRes-P	HA	
CICI	M	Birth	Unknown	36	14.5	21.5			Pulsar, Tempo+, R	CIS+		
CICJ	M	Birth	Connexin 26	35	10	25			HiRes, R	HiRes-P		
CICL	M	1;1	Connexin 26§	27	16	11			Freedom, Freedom, R	ACE (RE)		
CICM	M	Birth	Connexin 26	36	13	23			HiRes, PSP, R	‡		
CICN	F	Birth	Connexin 26	32.5	15.5	17			Freedom, Freedom, R	ACE (RE)		
CICQ	M	0;8	Usher Syndrome Type 1	31	14.5	16.5			Freedom, Freedom, R	ACE		
CICZ	F	0;2	Unknown	31	7	24			HiRes, PSP, R	HiRes-P w/ Fidelity 120	HA	
CIDB	F	0;11	CMV*	35	16	19			HiRes, PSP, R	HiRes-P w/ Fidelity 120	HA	
CIDS	M	0;3	Unknown	25	12.5	12.5			Freedom, Freedom, R	ACE		
CIDU	F	Birth	Unknown	28.5	13	15.5			HiRes, Auria, R	HiRes-P		

The abbreviation "HA" reflects children who use a hearing aid in the nonimplanted ear either consistently (CICE, CICZ) or intermittently (CIDB). Cochlear implant devices: N24, Freedom (Cochlear Corp.); HiRes (Advanced Bionics); Pulsar, C40+, Sonata (MED-EL Corp.).

**Children who have a history of acoustic hearing.*

§Children who have a history of progressive hearing loss as per parental report.

†Children who use implant processors with a body-level microphone.

‡Unknown speech-processing strategies for respective participants.

ID, identification.

Procedure

The children's CI speech processors were programmed by their audiologist before their visit, and testing was conducted under those conditions. Specific details regarding each child's implant and speech-processing strategy can be found in Table 1.

Children participated in a right–left discrimination task. This was a single-interval 2-alternative-forced choice task in which children needed to determine if the target stimulus was presented in the right hemifield or left hemifield of midline. Behavioral responses were measured using the observer-based psychophysical procedure (Olsho et al. 1987). This method is commonly used in infant psychoacoustics and has proven to be accurate in determining auditory sensitivity. For this study, the procedure was modified slightly so that spatial acuity could be assessed. On each trial, an observer, who was located in the observation room and unaware of the stimulus location, observed the children's behavior via a video feed. Each trial was initiated by the observer, who signaled to the computer to randomly present a stimulus on the right or left. This was done only when the children were quiet and looking forward, which was generally achieved by having a research assistant seated in the booth who directed the children's attention to the front loudspeaker by either waving a toy or engaging the children in a more active task (e.g., holding a block that was dropped into a bucket after the trial). After the stimulus presentation, the observer made a decision regarding the stimulus location (right or left) by watching the children's responses. Changes in behavior that were considered indicative of a response to the location of the stimulus included a head turn, shift in gaze, or changes in body position toward one side. If the observer chose the correct side of presentation, the children's response was reinforced by the presentation of a brief video segment from the computer monitor on the same side of stimulus presentation. For some children who seemed distracted during the task, the video segment was shown on the same side of stimulus presentation regardless of whether the observer was correct or incorrect to maintain their level of engagement in the task.

All children (except two) participated in the right–left discrimination task using their everyday listening mode. First, after completing Experiment 1 and 2 (given later) when using their BICIs, 17 out of 27 children in the BICI group repeated Experiment 2 with their first CI alone. Even fewer of these children (7 of 27) completed Experiment 1 using their first CI alone, most likely because of the fact that this was the last task of the session. Second, 3 out of 12 children in the UCI group used an HA in their contralateral ear with varied consistency. Attempts at quantifying performance under the bimodal (CI+HA) condition was attempted in two children (CICZ, CIDB), but performance was not greater than chance levels and therefore not reported here.

Performance on the right–left task was quantified in two ways. In Experiment 1, an adaptive-tracking method which varied source angle within the experiment was used to determine the smallest angle, relative to midline, that could be discriminated. In Experiment 2, source angles were fixed at ±50 degrees and a minimum of 10 trials were completed. The objective of Experiment 2 was to determine the level of performance among children who were unable complete Experiment 1 at above-chance levels.

Experiment 1: Right–Left Discrimination With Varying Source Angles • All three groups of children participated in this task. For the group of NH children, pairs of loudspeakers were placed at angles ranging from ±2.5 to ±50 degrees. These positions were selected after pilot testing revealed that small angles were necessary for this age group. For children with CIs, initial testing began with loudspeakers placed at angles ranging from ±10 to ±70 degrees. If adaptive tracking revealed that a child was consistently correct at ±10 degrees, the experiment was repeated with the smaller source angles (±2.5 to ±50 degrees). This was required for five of the children with BICIs.

On each trial, the angle was predetermined based on the set of rules outlined later, and the side (right or left) was randomized. Each adaptive track began at the largest angular displacement (±50 degrees or ±70 degrees). Data were collected using a 3-down/1-up adaptive method to vary the source angles from trial to trial, such that three consecutive correct responses resulted in decreased angle, and one incorrect response resulted in increased angle. Decisions regarding the step size leading to increased or decreased angles were based on rules similar to those used in adaptive procedures. Step sizes were doubled if an angle had been used twice and additional increase in angle size was required. Similarly, angle size was halved if an angle was used twice and additional decrease in angle size was required (Litovsky & Macmillan 1994; Litovsky 1997).

Each adaptive track was terminated once five reversals were reached or sooner if children became fussy or uncooperative. The a priori objective of this experiment was to complete one adaptive track for each condition. If, however, children were unable to complete an adaptive track because of fussiness, additional attempts to complete the adaptive track were made. There was a need to repeat testing with adaptive tracks in one or more conditions for 5 out of 12 children in the UCI group and 23 out of 27 children in the BICI group. The number of trials per adaptive track that yielded an MAA averaged 15 trials, and ranged from 8 to 27 trials. A typical adaptive track had a duration of approximately 5 min; however, this duration was influenced by the attention of the child and the amount of time needed between each trial.

The objective of this task was to estimate the MAA threshold, the smallest angle at which listeners can discriminate right versus left sound positions (Mills 1958). For each adaptive track, the MAA threshold was estimated using the Matlab psignifit toolbox, applying the methods described by Wichmann and Hill (2001a, 2001b). A logistic function was fit to all data points from each experimental run for each participant, using a constrained maximum likelihood algorithm. The MAA threshold was estimated at the point on the psychometric function intersecting with 80% correct. Because this method requires that listeners achieve a performance of 80% correct at one or more angular displacements, the MAA threshold could not be determined (CND) for children whose performance was <80% at all angles tested.

Children in the NH group completed the task with sound intensity roving (60 dB SPL ± 4 dB). Based on prior research with young bilaterally implanted children (e.g., Grieco-Calub et al. 2008; Godar & Litovsky 2010; Grieco-Calub & Litovsky 2010), we recognized the fact that the right–left discrimination task may be difficult for some of the children who use CIs, even with the intensity fixed. Therefore, in the BICI and UCI groups, performance was first measured with a fixed-intensity level, whereby monaural level cues in addition to interaural difference cues were available to the listener. When possible, regardless of performance in the fixed-intensity level condition, children repeated the task with a roving-intensity level. The success of obtaining results in the intensity-rove condition was dependent on the child's willingness to participate, the time it took to complete the other tasks during their visit, and their fatigue level. As a result, not all children were able to complete this task.

Experiment 2: Right–Left Discrimination, Loudspeakers Fixed (±50 degrees) • The adaptive-tracking version of the right–left discrimination task is an effective method for quickly estimating an individual's spatial acuity; however, it has some disadvantages. First, if the participant's performance is less than chance at all angles evaluated, an MAA threshold cannot be estimated and spatial acuity cannot be quantified. Second, the nature of the adaptive measure is to quickly target angles that are near threshold, which means that the number of trials per angle may be small. As a result, performance at larger or smaller angles outside of threshold is difficult to evaluate.

In our attempt to evaluate performance on right–left discrimination for all participants, children in the BICI and UCI groups completed the task with source angles fixed at ±50 degrees relative to midline. The ±50 degree locations were chosen because these angles were considered large enough to account for most of the variability observed in the adaptive version of the task, yet within the operating range of the directional microphones of CI-speech processors. Only children in the CI groups participated in this task because all of the children in the NH group completed the adaptive version of the task, even with intensity roving. Stimuli were presented at ±50 degrees for as many trials as the children would consistently respond to. The number of trials completed ranged from 10 to 39 (mean = 17).

As with the adaptive-tracking method, children were first tested with a fixed-intensity level of 60 dB SPL on each trial. When possible, the task was repeated with the 8 dB rove. Because of intersubject variability in attention span, and the resulting variability in the number of trials completed by the children, performance was normalized for individual participants. A method using principles of binomial distribution, which takes into account the number of trials completed by each participant, was applied with Equation (1):

$$\mathrm{SD} = \mathrm{sqrt}\ [(p * (1-p))/(\mathrm{n})]$$

$$\#\ \text{of SD above chance} = (\mathrm{x}-0.50)/\mathrm{SD}$$

where p = probability of correct answer (0.5), n = number of trials, and x = proportion of correct responses of the individual child.

RESULTS

Experiment 1: Varying Source Angles

Children in all three groups participated in the right–left discrimination task with varying source angles (adaptive-tracking method). Results were quantified by estimating the MAA threshold (see Figure 1). MAA thresholds for children in the NH group ranged from 3.3 to 30.2 degrees (mean ± SD = 14.5 degrees ± 10.5 degrees; Figure 1, *black circle*).

Because of the effect of intensity rove on MAA threshold (Litovsky et al. 2006a), children in the BICI and UCI groups were first tested on the right–left discrimination task with a fixed-intensity level of 60 dB SPL. The goal was to test these children with access to all spatial cues that might be naturally available, to potentially maximize performance. When using both devices, 17 out of 27 children in the BICI group had a measurable MAA threshold in the fixed-intensity level condition. MAA thresholds of these children were highly variable, ranging from 2.5 to 67 degrees (mean ± SD = 37.4 degrees ± 23.2 degrees; Figure 1, *white and gray circles*), thus substantially greater than values obtained in the NH group. Because of the large variance in performance within the BICI group, a t-test for independent samples failed normality. Thus, a Wilcoxon rank sum test for two independent samples was conducted. The analysis revealed a significant difference in MAA threshold between the BICI group with the intensity fixed and NH group with the intensity roved ($z = 7.67$, $p < 0.001$), suggesting that children in the NH group had significantly better spatial acuity, despite the minimization of monaural-level cues.

Also shown in Figure 1 (*white and gray circles*) are MAA thresholds for the roved-intensity condition. Of the 27 children tested on this task, 13 reached performance of ≥80% on at least one angle; thus it was possible to estimate MAA thresholds with intensity roving in this subset of children. Similar to the finding in the fixed-intensity level condition, there was large variability in performance. MAA thresholds ranged from 5.7 to 69.6 degrees (mean ± SD = 30.9 degrees ± 21.1 degrees). A paired *t*-test did not reveal a significant difference in the MAA thresholds obtained in the fixed-intensity and intensity-rove conditions [$t(11) = 0.347$, $p = 0.74$]. There was only one case (CIDM) in which MAA threshold was estimated in the condition with intensity rove but not with fixed intensity (data point "Y"). When compared with the performance of the NH group with intensity roving, only five children in the BICI group

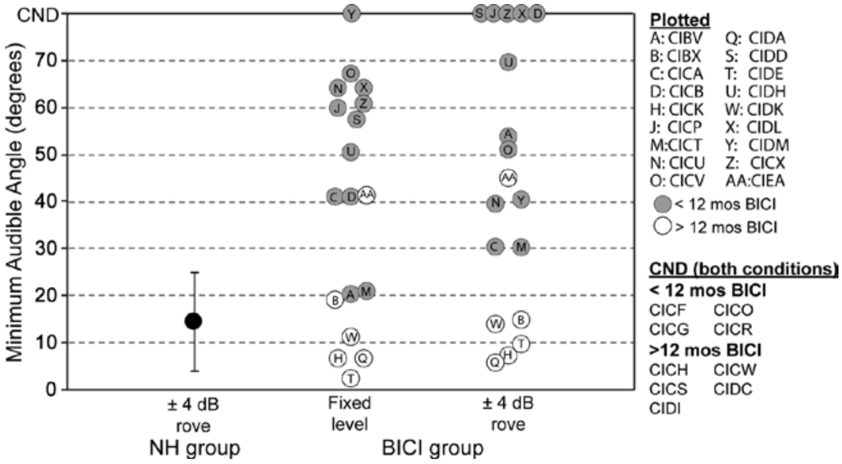

Fig. 1. Results from the adaptive version of the right–left discrimination task as quantified by MAA. Average performance (±SD) is shown for children who have normal acoustic hearing (*black circles*). Individual performance is shown for children in the BICI group with ≥12 mos (*white circles*) or <12 mos (*gray circles*) of BICI use. BICI, bilateral cochlear implant; CND, could not determine; MAA, minimum audible angle; NH, normal acoustic hearing.

performed within 1 SD of the NH group. It is interesting to note that all five of these children had >12 months of experience with their BICIs (*white circles*).

Figure 1 does not contain data from the following groups because the children within each group did not reach 80% correct at any one angle; thus MAA thresholds could not be estimated (see Methods): 9 of the 27 children in the BICI group when using their bilateral devices (Figure 1, "CND, both conditions"); the BICI group when they performed the task with their first CI alone; and the UCI group. There was one exception in the UCI group: CICN had an MAA of 69.3 degrees that was near the upper limit of the measurement.

Experiment 2: Fixed Source Angle, Fixed Intensity

Performance on the right–left discrimination task when using a fixed-angle method at a fixed intensity level was quantified for each participant in the BICI and UCI groups by determining the number of SDs above chance (see Methods, Equation 1). Using the number of SDs above chance as the dependent variable, one sample *t*-test revealed that the BICI group performed significantly above chance when using both devices [$t(26) = 5.3$, $p < 0.001$; Figure 2, *white and gray circles*]. A subset of children in the BICI group (N = 17) repeated the task with their 1st CI alone; however, their performance was at chance levels [$t(16) = 1.9$, $p = 0.7$; Figure 2, *squares*]. Children in the BICI group who completed both bilateral (Figure 2, *gray circles*) and unilateral conditions performed significantly better when using both devices than when using their 1st CI alone [$t(16) = 6.5$, $p < 0.001$].

The performance of the children in the UCI group was also at chance levels for this task [$t(11) = 1.1$, $p = 0.3$; Figure 2, *triangles*], although two children did score above 1 SD (CICN = 1.5; CICS = 2). Unequal N in between-subject analyses revealed that the performance of the UCI group was not significantly different from that of children in the BICI group when tested with their 1st implant alone [$t(27) = 0.5$, $p = 0.6$]. When using both implants, however, the BICI group performed significantly better than the UCI group [$t(37) = 3.9$, $p < 0.001$].

Experiment 2: Fixed Source Angle, Intensity Roving (±4 dB)

The final experiment was conducted to determine the effect of intensity roving on performance for the right–left discrimination task at fixed angles of ±50 degrees. Although the a priori objective was to collect data from all children in this condition, only data from the BICI group will be presented. Note that among the children in the BICI group, six were unable to complete the task with intensity roving (Figure 3A & 3B, "CND"). Children in the UCI group either did not perform significantly above chance (N = 2) or were not tested in this condition because of fatigue (N = 10).

The intensity roving had wide ranging effects on performance within the BICI group. To better identify trends in performance, results from the BICI group were divided based on whether children had less than or >12 months of experience using bilateral devices. The rationale for this division stems from prior work showing significant improvement on the right–left discrimination task following 12 months of listening experience in the BICI mode (Godar & Litovsky 2010).

Figure 3A illustrates data from children in the BICI group who had <12 months of bilateral experience. Out of the 10 children whose score was at least 1 SD above chance in the fixed-intensity level condition, only 3 (30%) demonstrated a similar ability to discriminate right versus left when the intensity was roved by ±4 dB. With the exception of one participant, children who scored <1 SD from chance in the fixed-intensity level condition (N = 6) either continued to perform at chance levels (N = 2) or could not complete the task in the intensity-rove condition (N = 3). Contrary to the group trend, participant CIDM ("Y") performed notably better in the intensity-rove condition compared with the fixed-intensity condition.

Performance among the children who had ≥12 months of bilateral experience was generally better. Nine children's performance was >1 SD above-chance levels in the fixed-intensity level condition (Figure 3B). Of those, seven (78%) had a similar level of performance when the intensity was roved. Taken together, these data are consistent with previous reports in older children showing that longer use of BICIs results in better performance on the right–left discrimination task (Godar & Litovsky 2010).

Relationship to Subject Variables

Previous reports have suggested that age of bilateral activation (Van Deun et al. 2010) and duration of bilateral CI use (Godar & Litovsky 2010) have contributed to better spatial-hearing skills in older children (ranging 4 to 15 years of age) who use BICIs. To determine if these variables related to the spatial acuity of the 2-to-3-year-old BICI users in the present study, multivariate linear regression analyses were conducted for the following four dependent variables: MAA threshold (fixed-intensity level condition); MAA threshold (intensity-rove condition); performance on the right–left discrimination task fixed at ±50 degrees (fixed-intensity level condition); perfor-

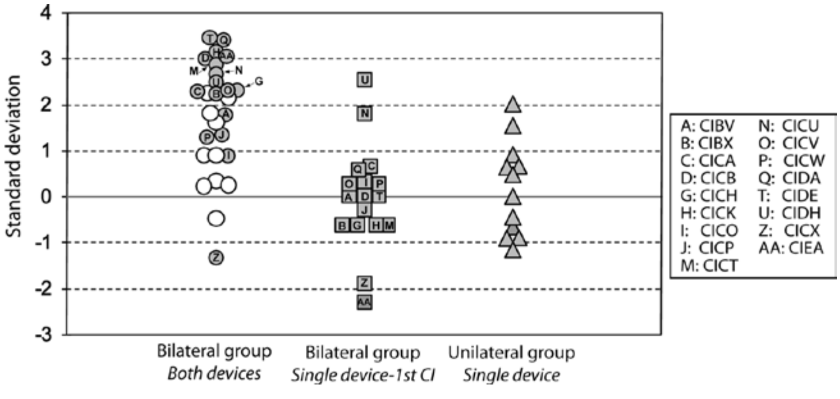

Fig. 2. Results from the right–left discrimination task with source angles fixed at ±50 degrees with a fixed intensity level of 60 dB SPL. Children within the BICI group were divided based on whether they repeated the task with their first CI alone (*gray circles*) or did not (*white circles*). CI, cochlear implant; BICI, bilateral cochlear implant.

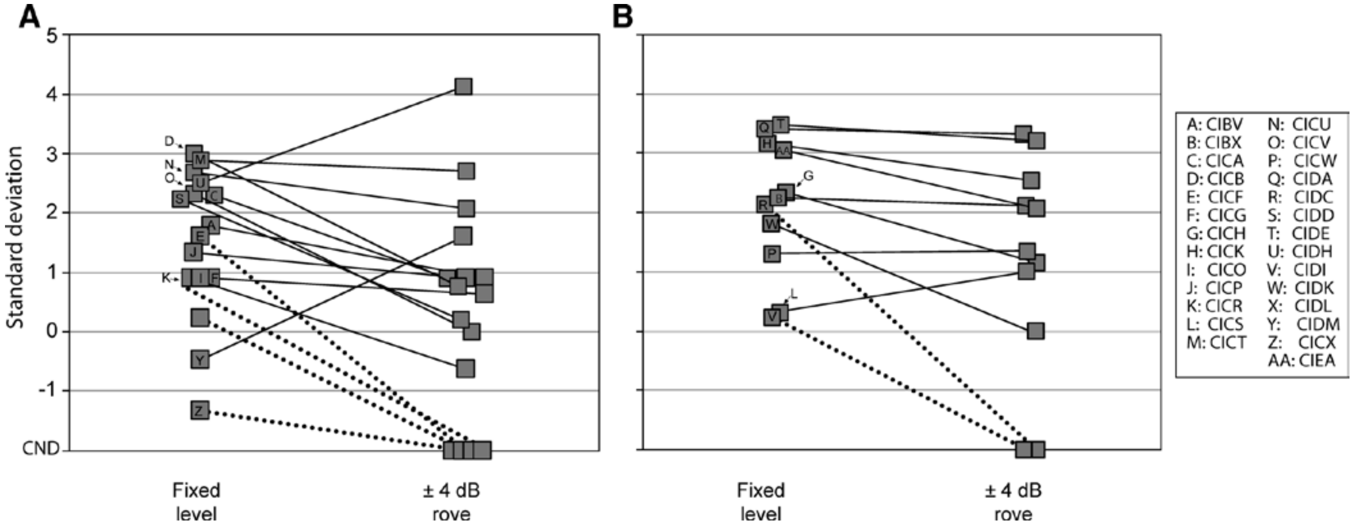

Fig. 3. Results from the right–left discrimination task with source angles fixed at ±50 degrees with fixed intensity level of 60 dB SPL and with an intensity rove of ±4 dB from the BICI group. A, Results from children with <12 mos of BICI experience. B, Results from children with ≥12 mos of BICI experience. Solid lines represent data from children who completed the task in the fixed-intensity level and intensity-rove conditions. Dotted lines represent data from children who have a data point for the fixed-intensity level condition only. BICI, bilateral cochlear implant; CND, could not determine.

mance on the right–left discrimination task fixed at ±50 degrees (intensity-rove condition). Initially, seven variables were identified as possible predictors of performance: the children's age at visit, age at first implant activation, age at second implant activation, duration of hearing experience, duration of bilateral implant use, history of acoustic hearing (present or absent), and CI device (Cochlear Americas, Advanced Bionics, Med-El). Because a history of acoustic hearing and CI device were not equally represented across the sample, these two variables were excluded from the models. Results of the four analyses indicated that none of the included variables were found to be significant predictors either of MAA threshold when the intensity was fixed [$F(3,13) = 2.46$, $p = 0.109$] or roved [$F(3,9) = 1.61$, $p = 0.254$] or of performance on the right–left discrimination task fixed at ±50 degrees when the intensity was fixed [$F(3,23) = 0.49$, $p = 0.694$] or roved [$F(3,16) = 0.92$, $p = 0.454$].

DISCUSSION

This study presents novel findings from children with BICIs in that we focused on relatively young bilaterally implanted children. The results presented here add to a growing body of literature showing that, on average, children with BICIs can develop some ability to use spatial cues. Neither these children nor their peers who use UCIs were able to achieve the same level of performance when using their first CI alone.

Spatial Acuity in Children With NH and Children With BICIs

Results of this study show that 2-to-3-year-old children who have NH are developing the spatial-hearing skills necessary to perform the right–left discrimination task even when monaural level cues are minimized with intensity roving. The MAA thresholds obtained in this study, however, were higher than those previously reported for children of this age (e.g., Morrongiello & Rocca 1990; Litovsky 1997), most likely because of effects of the level rove. Consistent with these previous reports of MAA thresholds in young children, results of this study suggest that spatial acuity has not matured by 3 years of age. The observation that MAA thresholds are relatively small, however, provides a reasonable anchor against which to compare the data from children who use BICIs.

Consistent with previous work in older children and adults with BICIs (e.g., van Hoesel & Tyler 2003; Litovsky et al. 2006c; Litovsky et al. 2009; VanDuen et al. 2010; Grieco-Calub & Litovsky 2010), there continues to be a large range of individual variability in performance among children who use BICIs that was not observed in their peers with NH. The large variability in performance, coupled with a somewhat small sample size, most likely places limits on our ability to identify any participant variables that were related to performance, both when the source angle varied and when it was fixed at ±50 degrees. Larger-scale studies with tighter control on participant variables when possible might be able to identify predictors of outcomes. The observation that the field, in general, has not come to a consensus about what variables might or might not contribute to success suggests that there may be more than one factor, or a complex interaction of factors, that will determine outcomes.

Inspection of Figures 1 and 3 would suggest that duration of bilateral experience does influence results, particularly when monaural cues are limited (as in the case of intensity roving). In the intensity-rove condition, five children with BICIs had MAA thresholds within 1 SD of their peers with NH. All five of these children had >12 months of BICI experience (Experiment 1). In addition, a larger percentage of children with ≥12 months of BICI experience performed at above-chance levels when source angles were fixed at ±50 degrees even when the intensity was roved, compared with a smaller number of children from the group with <12 months of BICI experience who were able to do so (Experiment 2). The caveat to these findings, however, is that out of the children with BICIs who could not perform above chance when source angles were adaptively varied, four had <12 months of BICI experience and five had ≥12 months of BICI experience. Taken together, these results would suggest that if children can discriminate right versus left, they will tend to get better with more bilateral experience. However, the duration of BICI use alone is not predictive of performance.

Unilateral Experience

Unlike the variability observed in the BICI group, there was little difference in performance on the right–left discrimination task among the children in the UCI group. Only one (CICN) of the unilaterally-implanted 2-to-3-year-old children was able to perform right–left discrimination using the adaptive-tracking method; however, this was under the fixed-intensity level condition and, even then, the MAA threshold was essentially at the limits of our measurement (69.3 degrees). On the fixed-angle task at ±50 degrees, CICN as well as CICS were the only two children in the UCI group who scored >1 SD above chance with a fixed-intensity level. It is interesting to note that CICS was not able to show this level of performance on the right–left discrimination task with varying source angles. Reasons for the observation that these two children outperformed the other UCI users in this study are unclear. Potential factors that could influence performance would be consistent use of a HA on the contralateral (i.e., nonimplanted) ear, longer durations of CI use, or experience with acoustic hearing before deafness. None of these factors, however, apply to these two children (see Table 1).

The findings in the present study do not rule out the possibility that all of the children in the UCI group will be able to develop a sense of spatial awareness with additional unilateral experience. It is important to note that the cohort of children in the UCI group had between 11 and 24 months of auditory experience at the time of testing, which is appreciably smaller than the duration of unilateral experience of adults and older children who exhibit spatial-hearing skills in previous studies (Grantham et al. 2008b; Grieco-Calub & Litovsky 2010). The degree to which these children will be able to develop age-appropriate spatial acuity, however, is unknown.

Auditory Plasticity

Manipulation of auditory experience during early development can induce abnormal auditory physiology, either at the level of a single neuron (Seidl & Grothe 2005) or in sound localizing behavior (King et al. 2000). These forms of auditory plasticity are observed primarily in juvenile animals, and generally not in adults (but see Linkenhoker & Knudsen 2002), consistent with the idea of a sensitive period for acquiring spatial hearing. In support of this, BICIs tend to promote better spatial hearing in postlingually deafened individuals than in adults and children who were deaf at birth or shortly thereafter (e.g., Litovsky et al. 2004; Litovsky et al. 2006c). In addition, adults with postlingual deafness have better sensitivity to interaural timing differences (ITDs) compared with adults with prelingual deafness (Litovsky et al. 2010). Taken together, early auditory experience seems to be necessary for establishing the appropriate binaural connections involved in the development of spatial hearing.

One of the goals of this study was to determine whether providing bilateral auditory input at a young age, when neural plasticity is great, would influence the emergence of spatial acuity. The observation that a few of the children in the BICI group had spatial acuity skills equivalent to their chronologically age matched acoustic hearing peers and that none of the children in the UCI group performed comparably suggests that earlier bilateral activation will influence the maturation of spatial hearing. This is not to say that the children in the BICI group who performed similarly to their acoustic hearing peers would not have reached the same level of performance if they received their BICIs later (i.e., had longer duration of unilateral experience). However, minimizing the delay of bilateral activation most likely resulted in the observation that their spatial acuity skills were age appropriate by 3 years of age. As a consequence, the development of more complex spatial-hearing skills may also follow a normal developmental trajectory.

Limitations of BICIs

Although the benefits from bilateral CI use are being documented, there remains a gap in performance between children who use BICIs and children who have normal hearing. A number of other technical factors are likely candidates in accounting for this gap in performance, including: (1) a lack of fine-structure in the incoming signal, therefore absence of low-frequency ITD cues, (2) the absence of a commercially available binaural processor that can preserve cues such as ILDs or ITDs in the envelopes of the signal and present them to the user with fidelity, (3) the absence of coordinated compression by the microphones at the two ears, (4) a likelihood of mismatched insertion depth in the two ears, leading to a mismatch in auditory nerve fibers stimulated in the two ears for the same range of frequencies, and (5) the fact that children with BICIs undergo periods of auditory deprivation not experienced by normal-hearing children.

Considered together, it is clear that the use of BICIs does not guarantee access to the binaural cues thought to be important for these complex tasks like spatial hearing. Today's commercially available CI devices are designed for one ear and as such are unable to coordinate the auditory input to the two ears. In addition, there are no standard guidelines to fitting independently functioning CIs bilaterally. Such protocols may optimize the availability of bilateral information necessary for spatial hearing.

Despite this, the data presented here support the notion that individuals with BICIs have access to monaural cues in either ear and can exploit at least some of the binaural cues that individuals with NH rely on for a number of spatial hearing tasks. Most likely, BICI users depend on interaural-level cues; the extent to which the BICI users depend on interaural timing cues of the signal envelopes, however, seems minimal (Laback et al. 2004; van Hoesel 2004; Seeber & Fastl 2008; Grantham et al. 2008a).

Microphone Placement

Consistent with prior studies is the fact that the CI microphones on the majority of the participants were not placed inside the ear canal but rather behind the ear. Of the cohort of children in the BICI group, however, five were tested when using a speech processor that placed the microphone at body level (CICG, “F”; CICH, “G”; CICW, “P”; CIDI, “V”; and CIDL, “X”). On the right–left discrimination task when using the adaptive-tracking method, all children, except CIDL, with body-level microphones were unable to perform above chance; CIDL had an MAA threshold of 64.2 degrees in the fixed-intensity level condition only, which was the second-largest MAA threshold among the participants. For the task with source angles fixed at ±50 degrees, only CICH and CICW scored at least 1 SD above chance in the fixed-intensity level condition.

They were able to maintain this level of performance when intensity roving was introduced. It is important to note that both of these children had >12 months of bilateral experience.

There is no evidence that placement of a CI microphone off the head, compared with a behind-the-ear placement, interferes with intended outcomes of CI use such as spoken-language development, spoken-language comprehension or educational outcomes. With regard to interaural cues, microphone placements on or off the head seem to maintain interaural-level cues that arise primarily from the shadowing of the signal by the head, at least for some patients (Ricketts et al. 2006; van Hoesel 2004). The caveat to those findings, however, is that front-end compression within the speech processor compromises the ILDs in other patients; this latter finding would potentially impair spatial hearing and possibly other auditory skills that depend on interaural cues in implant users.

A conclusion about the benefits or disadvantages of body-level processor microphones cannot be made from the data presented here. Spatial hearing is, however, an acquired skill that is dependent on the listener's experience with consistent interaural cues. It is not unreasonable to speculate that providing an inconsistent cue via a body-level microphone, because of varying placement on the child's body from day to day, may impede this development. It is important to note that the five children who used body-level microphones were among the poorest performers on the adaptive-tracking version of the right–left discrimination task. Even though three out of the five children had >12 months of BICI experience, their performance did not reflect this experience. Whether or not microphone placement is a factor to the long-term outcomes with BICIs needs to be investigated further.

Strengths and Limitations of the Present Project

This study provides behavioral spatial-hearing data on 2-to-3-year-old children, a population that is often difficult to test because of the lack of age-appropriate methodology. The use of the observer-based psychophysical procedure in this study provides an effective method of determining spatial acuity in young children who either have NH or who are CI users. There were, however, some limitations to the data presented here. First, not all children were able to complete every condition. Reasons for this may include task difficulty, fatigue, and boredom. These reasons may also have contributed to the variability in performance as well as a potential underestimation of spatial acuity in some children. For example, the lack of response from a child could mean either that he/she could not lateralize the sound-source location (inability) or that he/she just didn't respond (the child had the ability but was unwilling to respond). Possible evidence of this was seen in participants who scored better in more complex tasks (i.e., when intensity roving was present) than in easier tasks. One participant (CIDM), however, consistently performed *better* when intensity roving was implemented. Whether this finding reflects a complex interaction between the discrimination of monaural- and interaural-level cues or whether it reflects an inconsistent attention component is unclear and will need to be investigated further.

Anecdotally, we made two general observations over the course of this study that may give light to some of the results. First, children who seemed to understand the task at the onset (i.e., who could localize the first stimulus they heard) were better able to stay on task. Second, when the task demands increased (i.e., having the children in the BICI remove their second CI), many children disengaged from the task by misbehaving or not responding. Upon returning to a bilateral listening mode, their willingness to stay on task improved. Taken together, these observations would suggest that the children were better able to stay on task when they understood what was happening and were consistently being reinforced. When the task demands were too high, the children essentially stopped participating. Developing additional age-appropriate methods to use with children under the age of 3 years would be helpful in further elucidating spatial-hearing skills in this population of children.

Final Note

The observation that a greater number of children in the BICI group relative to the number of children in the UCI group have spatial acuity that approximates that of their acoustic hearing peers suggests that there seems to be a benefit in providing bilateral input at a young age. There continues, however, to be large variability in overall outcomes; the reasons for this are still unclear and need to be more systematically studied.

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