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Reaching for Sound Measures: An Ecologically Valid Estimate of Spatial Hearing in 2- to 3-Year-Old Children With Bilateral Cochlear Implants

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Hypothesis: A novel reaching for sound (RFS) methodology can yield a high level of spatial hearing ability in 2- to 3-year-old children with normal hearing and with bilateral cochlear implants (BiCIs).
Background: A growing number of children who are deaf are receiving BiCIs at a young age. Their spatial hearing abilities are emerging but highly variable within the population. Our novel reaching for sound method uses an ecologically valid approach that engages children and maintains their motivation. The present work was aimed at using the novel RFS method to evaluate spatial hearing in 2- to 3-year-olds with normal hearing and with BiCIs.
Methods: Six children with BiCIs and 15 children with NH, ages 2 to 3 years participated. In the BiCI group, testing was performed in bilateral or single CI (unilateral) conditions. Loudspeakers were separated by ±60, ±45, ±30, or ±15 degrees. On each trial, a small toy was hidden behind one of the loudspeakers, and the child's task was to reach through a hole in the curtain above the loudspeaker, to indicate source location. Children were reinforced for correct responses. At each angle, the ability of the child to reach criterion of 80% or greater correct was assessed.
Results: All BiCI users reached criterion at all angles tested in the bilateral condition; however, performance was poorer when using a single CI. Of the 15 NH children, 13 were able to perform the task accurately and reached criterion at all angles.
Conclusion: Spatial hearing skills studied with the RFS method revealed novel findings regarding the emergence of sound localization in very young BiCI users. **Key Words:** Bilateral—Binaural—Children—Cochlear Implants—Sound localization—Spatial.

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One of the most rudimentary and functionally important aspects of human development is the emergence of auditory spatial hearing. The ability of a young child to identify the location and content of sound sources is an essential component of their ability to integrate percepts regarding objects in the world efficiently and effectively. Spatial hearing depends on the integration of inputs from the 2 ears by neural mechanisms that are specialized for this task; the binaural auditory system in normal hearing (NH) listeners is somewhat refined by age 4 to 5 ((1,2) for review); thus, young children have access to spatial cues that enable them to localize sounds and segregate speech from noise (3).

The situation is somewhat different in children who are born deaf and receive cochlear implants (CIs). Although single CIs were the standard of care for many years, in the recent decade, bilateral CIs (BiCIs) have been provided to a growing number of children. The motivation has been, at least in part, that 2 CIs will enable these children to function significantly better on spatial hearing tasks compared with their performance with a single CI. Spatial hearing skills can be measured in children older than 4 years using a variety of methods, including source identification method, whereby the target stimulus varies in location from among a set of loudspeakers and the child is asked to point to the perceived location of the sound source. In a recent study (4) with 21 children using BiCIs, 11 of 21 children had root mean square (RMS) errors that were smaller when they used both CIs than when a single CI was activated, suggesting that they experienced a bilateral benefit. When using both CIs, performance was highly variable among the 21 children; RMS errors ranged from 19 to 56 degrees, compared with the 5-year-old NH group who had RMS errors ranging from 9 to 29 degrees. Similar differences between CI users and NH children were found by van Deun and colleagues (5).

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Another approach to measuring spatial hearing skills in children is to use a discrimination task, whereby auditory stimuli are presented right versus left, and the measure of spatial sensitivity is the minimum audible angle (MAA) (6,7), the smallest change in the location of a sound that can be reliably discriminated. Using the MAA, bilateral performance is also significantly better than unilateral performance, and spatial hearing acuity improves with experience after activation of bilateral hearing (8,9). Children ages 4 and older can reach MAA thresholds as low as 5 to 10 degrees after about a year of bilateral listening experience, with little or no change in their ability to perform the task when using a single CI. However, there is notable intersubject variability such that some children's performance is still considerably poor in the bilateral listening mode, even after a year or more of experience (4).

In studies discussed thus far, children received their second CI typically by age 4 years, often with several years between the activation of the first and second CI. There is an open question as to whether the gap in performance between children with BiCIs and NH is due to the later age of bilateral activation. Grieco-Calub and Litovsky (10) have demonstrated that a number of toddlers whose second CI was activated by age 18 months showed MAA thresholds that are within the range of NH toddlers. Although the MAA measure is excellent for demonstrating spatial hearing acuity, it does not provide information regarding the ability of a listener to develop a spatial hearing map per se.

The present study was concerned with the implementation of a novel task that enabled us to measure spatial hearing in toddlers who use BiCIs. This RFS method was modeled after a successful series of experiments in which spatial hearing was assessed in NH infants by eliciting reaching behaviors in the dark. In these "reaching in the dark" studies, infants were trained to reach for sounding objects, and their ability to find the object (such as a rattle sound) in the dark was studied under infrared lighting. In a 5-loudspeaker array on the horizontal plane, infants as young as 5 to 6 months of age reach accurately on the first attempt on nearly 60% of trials when sounds are within reach (11). When sounds are varied by distance, infants discriminate near versus far stimuli with their reaching behavior (12). Here, we implemented a "reaching in the light" task whereby the sounding objects were obscured by a curtain. This task was designed for versatility, for example, the number of possible locations can be varied from 2 to 9 so that either discrimination of source location, or spatial hearing per se, can be measured. In addition, the task, whereby young children reach for sounding objects, is versatile; for example, it can be applied to measures of speech perception and discrimination (13).

The purpose of this study was to use the RFS methodology to evaluate spatial hearing discrimination in toddlers who are fitted with BiCIs and to determine whether their performance on the task is better in the bilateral versus unilateral listening conditions. A secondary purpose was to compare these results with results from toddlers who are in the same chronological age range, whose hearing is normal.

MATERIALS AND METHODS

Participants

This preliminary study reports results from 6 children with BiCIs, all of whom had at least 1 year of experience with the first CI, were native English speakers, had no diagnosed developmental disabilities, and their primary mode of communication was oral. Their age at the time of testing ranged from 34 to 42 months, with amount of bilateral experience ranging from 5 to 25 months. Table 1 shows demographic data regarding the age of implantation for each ear, cause of deafness, type of CI devices used, and so on. In addition, 15 children with normal hearing (NH) were recruited, whose ages ranged from 24 to 34 months. None had known developmental disabilities, hearing loss, illness or ear infections on the day of testing. Table 2 shows their ages and results from tymanometric measures on day of testing.

Experimental Setup

Testing was conducted in a standard IAC sound booth (2.743 × 3.658 m) with reverberation time T_{60} of approximately 250 ms. A semi-circular testing apparatus (radius of 0.6 m) with 9 holes, spaced 15 degrees apart from −60 to 60 degrees. Each hole had a diameter of 11 cm. Loudspeakers (Cambridge SoundWorks Center/Surround IV, North Andover, MA, USA) were positioned under each hole such that they were at ear level when the child was seated but invisible to the child as they were hidden behind acoustically transparent curtains. The child sat in a chair facing the apparatus and could see the holes in the curtain, as well as any objects that were positioned above the curtain at the beginning of each trial to draw the child's attention to the 0-degree front location. One experimenter sat next to the child, a second experimenter was behind the apparatus to manipulate the objects being hidden, and a third experimenter was in the observation room coding responses. Depending on the experimental condition, a different curtain was used, so that the number and locations of loudspeakers could be manipulated (see below for details).

Two video cameras were used to record the child's responses and code the data. Online coding was conducted to determine

TABLE 1. *Biographical data for normal hearing children*

Subject code	Age (mo)	Tympanometric screening
COO	31	Pass
COR	24	Child would not participate
COS	31	Pass
COT	31	No tymp R; Peak Ytm = 0.2 L
[a]COQ	31	No tymp L; Flat R
COV	33	WNL R; Peak Ytm = 0.2 L
COW	32	Pass
COX	34	Low peaks Au
[a]COZ	25	Pass
CPF	34	Pass
CPH	34	No tymp L; R WNL
CPK	33	WNL L; PE tube R
CQC	33	Pass
CQD	32	Pass
CQE	32	Pass
AVERAGES	31	

[a] Did not pass criteria at 30 and 15 degrees (COQ) and at 15 degrees (COZ).

TABLE 2. *Biographical data for children with cochlear implants*

Subject code	Sex	Age of ID	Etiology	Age at visit (mo)	Age of first CI (mo)	Unilateral experience (mo)	Age of second CI (mo)	Duration of BICI (mo)	First CI (Internal device, processor, ear)	Second CI (Internal device, processor, ear)
CIEP	F	Birth	Connexin 26	34	13	16	29	5	Sonata, OPUS2, Right	Sonata, OPUS2, Left
CIEQ	F	10 d after birth	Genetic	34	10	1	11	23	PSP Body Worn processor (mics e magnet), Right	PSP Body Worn processor (mics e magnet), Left
CIER	M	6 wk	LVAS	38	19	0	19	19	Sonata, OPUS2,	Sonata, OPUS2,
CIEY	M	Birth	Connexin 26	37	12	1 week	12	25	Contour Advance, Freedom, Right	Contour Advance, Freedom, Left
CIEZ	M	2 mo	Meningitis	42	13	20	33	9	PSP Body Worn processor (mics e magnet), Left	PSP Body Worn processor (mics e magnet), Right
CIFB	F	14 mo	Unknown	39	20	1 week	20	19	Freedom, Nuc5, Right	Freedom, Nuc5, Right

whether a child met criteria at particular locations and was used to determine whether smaller angles would be used. Offline coding was used to determine interrater reliability. A camera positioned behind/above the child was used to monitor the child's behavior from a bird's eye view, and a second camera positioned above the loudspeaker at 0 degree facing the child was used to monitor eye gaze and head orientation. Audio stimuli were stored as .wav files and played to the loudspeakers through Tucker-Davis System hardware (TDT). Customized software for running the program and data collection were written in MATLAB programming language.

Stimuli

The stimulus was selected after extensive piloting, in which the duration and frequency bandwidth were varied. The final decision was to use a stimulus that attracted the children's attention and produced reliable responses. The stimulus consisted of a recorded female voice saying the carrier phrase "When I hide I say…" followed by three 250-ms bursts of white noise presented at a rate of 4 per second. Stimuli were presented at a fixed level of 60 dB SPL (A weighting).

Testing Conditions

This study focused on the ability of 2- to 3-year-old children to discriminate between sound sources positioned in the frontal azimuthal plane. Children with BiCIs were tested when using either both CIs (bilateral) or a single CI (unilateral). NH children were tested in their natural "binaural" condition.

Training

Before testing, each child entered the observation room next to the sound booth and played a "peek-a-boo" game. The child selected a rewarding object such as a finger puppet and was taught that when they hear the experimenter voice "when I hide I say tch tch tch," the reward would disappear behind the curtain, and if the child reached through the hole in the curtain they would find the object. All children in this study reached readily, thus it was determined that they understood the task. Pretest training was then conducted in the testing booth. Stimuli were presented randomly from right or left at 60 degrees, and the child was exposed to stimuli from either side with equal probability. Each child first experienced a "directed reach" whereby the child was led hand-over-hand to reach through the curtain into the hole. This was performed for both sides. Based on the child's comprehension of the task, additional directed reach trials might have been required. In addition, if the child did not seem to comprehend that task, the experimenter behind the curtain paired the presentation of the reinforcer with the auditory stimulus presentation, and the experimenter sitting next to the child directed their attention to the stimuli, to reinforce the pairing of the visual and auditory stimuli.

Spatial Hearing Testing

After the training phase, spatial hearing testing was conducted. Children were seated on a chair facing the semicircular apparatus and were tested on their ability to discriminate between sounds presented from the right versus left. Children were first tested with bilateral devices, and subsequently in the unilateral listening mode (with their first CI or the right CI if implanted simultaneously). Each trial began with the toy held above the loudspeaker at 0-degree front. Once the experimenter was confident that the child's attention was drawn to that location, a prerecorded stimulus was presented from a target loudspeaker, and the toy was withdrawn. The stimulus consisted of a female voice saying "when I hide I say…" followed by 3 bursts of white noise (each burst had a duration of 250 ms with rise/fall times of 10 ms, presented at a rate of 4 per second). The child's task was to find the hidden toy by reaching into the hole that the child perceived to be spatially associated with the location of the toy. A trial was terminated either once the child reached through a hole (whether correct or incorrect), or if no reach occurred and the child lost interest, typically 8 to 10 seconds after the stimulus was presented. A trial was considered invalid if there was no reach. These trials were repeated, and their incidence is reported below. If the child reached into the correct hole, they were immediately reinforced as the object was in their hand for manipulation and exploration. If the response was incorrect, that is, the child reached into the hole on the opposite side, the reinforcer was brought into view from the correct curtain hole.

Testing began with the widest angular separation (60 degrees left/right). For each pair of right-left loudspeaker locations, a criterion of 80% or greater correct (statistically above chance for the number of trials used) had to be reached before proceeding to a smaller set of angles. This required that correct responses were made on 4 of 5 consecutive trials. Thus, throughout a block of trials, the computer calculated a running average of percentage correct for the most recent 5 trials. Once 80% was reached, testing for that set of positions was terminated. The possible right-left location pairs were: ±60, ±45, ±30, and ±15 degrees. If criterion was passed at ±60 degrees, testing continued at ±30 degrees; if criterion was passed at ±30 degrees, testing continued at ±15 degrees; if criterion was failed at ±30 degrees, testing continued at ±45 degrees; if criterion was then passed at ±45 degrees, testing resumed at ±30 degrees and so forth.

RESULTS

Of the 15 children with NH, 13 children reached the criterion of 80% or greater correct at all angles tested, 1 child did not do so at ±15 degrees, and another child did not at either ±15 or ±30 degrees. These are shown in Figure 1 as panels A, B, and C. In the latter 2 cases, there are no particular indicators that demarcate the children as being "different," developmentally; neither child was ill. However, informal observations suggest that their attention on the task was perhaps less focused, and they did require a greater number of trials to reach criterion than the other 13 children (see below).

Figure 2 shows the left-right discrimination results for the 6 children with BiCIs. Each panel shows results for a single child, comparing their bilateral (filled symbols) with unilateral (open symbols) performance. All 6 children reached the 80% or greater correct criterion when listening bilaterally, for all right-left loudspeaker separations; thus, when listening bilaterally, their performance was similar to that of the 13 of 15 NH children who passed criterion of 80% or greater correct at all angles (Fig. 1A). In contrast, when listening with a single CI, these children varied on the extent to which they were able to perform the task at 80% or greater correct. Two children were not able to perform the task at any of the angles; 2 children were able to perform the task at the larger angles but not at the smaller separation of ±15 degrees (similar to Fig. 1B), and 2 children were able to perform the task only at the largest angle of ±60 degrees (similar to Fig. 1C).

In addition to assessing the overall percent correct, we were interested in the number of trials that it took for children in the NH and BiCI groups to reach criterion of 80% or greater correct. For the BiCI group, this value was calculated for the bilateral conditions, on which all children reached criterion for all locations. Figure 3 shows average (±SD) number of trials to reach criterion, for the NH group and for the BiCI group tested bilaterally. Conditions on which criterion was not reached are not included. Individual children's data are show in Figure 3 (panel A), rank ordered by number of trials but sorted by the group to which they belonged (dark bars = NH; gray bars = BiCI). Group average (±SD) are shown in Figure 3 (panel B); these values were 20.3(±9.9) and 53.8 (±25.1) for the NH and BiCI groups, respectively, and were significantly different according to a Mann-Whitney rank sum test ($T = 97$; $p < 0.016$). This result suggests that, although the children with BiCIs generally reached the same level of performance when considering overall percent correct for right-left discrimination, they may have found the task more challenging, and required longer exposure to the task to be able to reach that level of performance.

As mentioned previously, some trials were considered invalid, and the trial was repeated at the end of the sequence. One potential interpretation of these trials is task difficulty, although they might also reflect attention to the task. Figure 4 shows the percent of trials that were considered to be valid, for the children with NH and BiCIs, taken only from the conditions on which children reached criterion. Individual children's data are shown in Figure 4 (panel A), rank ordered by number of trials but sorted by the group to which they belonged (dark bars = NH; gray bars = BiCI). Group average (±SD) are shown in Figure 4 (panel B); these values were 86.6 (±14) and 76.1 (±9.6) for the NH and BiCI groups, respectively, and were significantly different according to a Mann-Whitney rank sum test ($T = 34$; $p < 0.014$).

DISCUSSION

The present study was concerned with the emergence of spatial hearing skills in young children who are born deaf and receive cochlear implants in both ears at a relatively young age. The age of bilateral implantation has been reduced considerably in recent years, in the United States

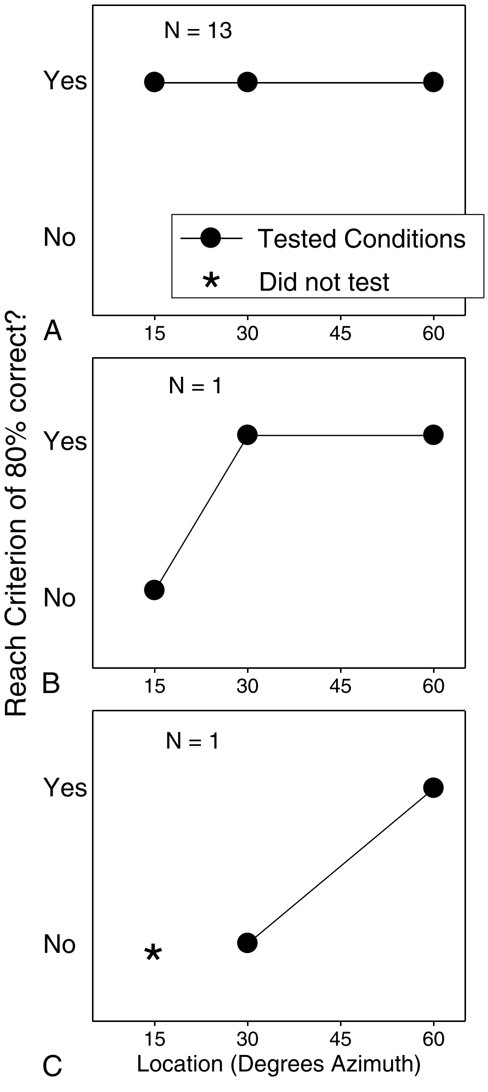

FIG. 1. Discrimination results from 15 NH children are summarized, grouped according to performance, including 13 children who passed criterion (≥80% correct) at all locations (*A*), one child who passed criterion at ±60 and ±30 degrees but not ±15 degrees, and 1 child who passed criterion at ±60 degrees but not ±30 degrees (±15 degrees not tested. Results are shown for the tested conditions (filled symbols), and untested angles are marked with the * symbol.

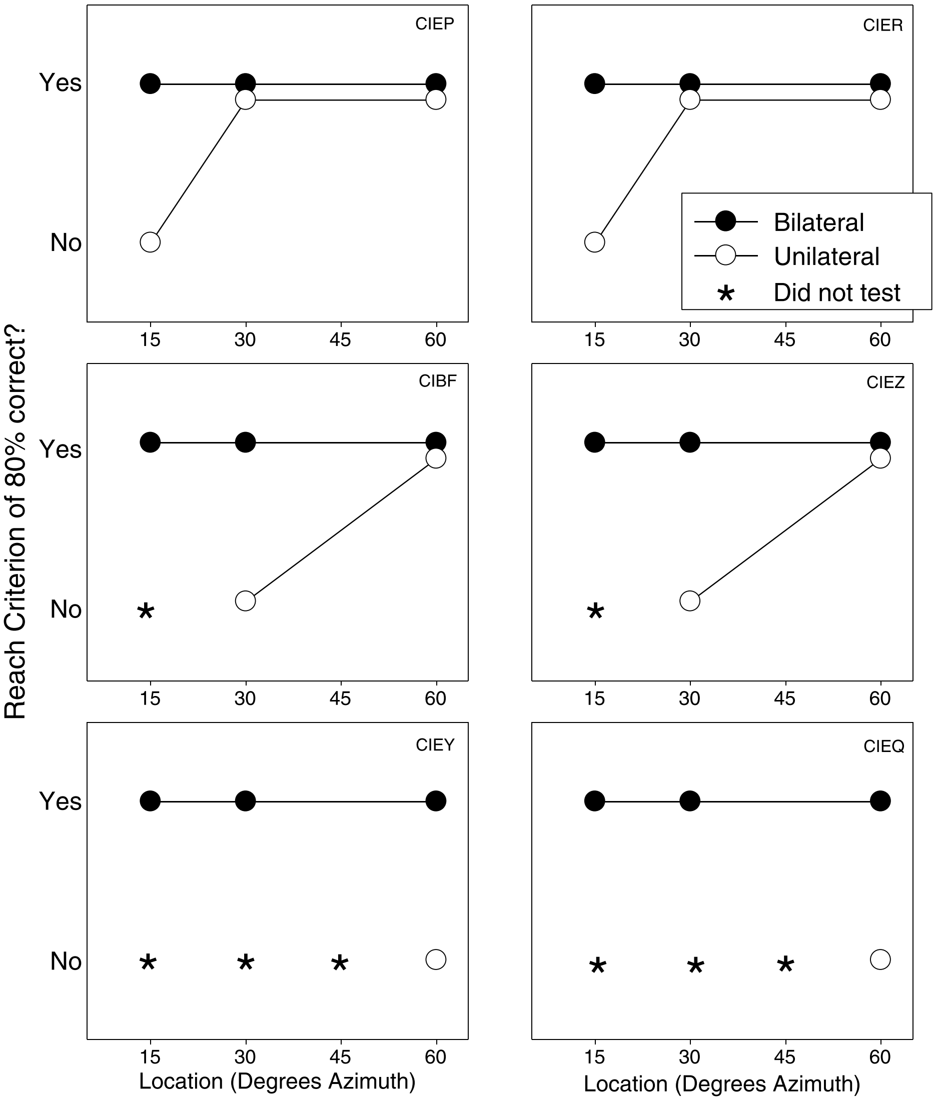

FIG. 2. Discrimination results from 6 children with bilateral cochlear implants (BiCIs) are shown, with data from 1 child in each panel. Data points indicate whether a child passed criterion (≥80% correct). Results are shown for the bilateral (*filled symbols*) and unilateral (*open symbols*) listening conditions; untested angles are marked with the * symbol.

and numerous other countries. However, the emergence of spatial hearing benefits in these young children remains to be fully understood. In a recent study (10), 26 bilaterally implanted children and 10 unilaterally implanted children were tested at age 2.5 years on the MAA task. Although some of the children with BiCIs performed similarly to their NH peers, performance of the children with cochlear implants was not uniform. We questioned whether the "looking while listening" paradigm is ideal for testing 2.5-year-olds in terms of motivation and interest in the task. In this experiment, we thus implemented a novel RFS method (11,12). This task was modeled after "reaching in the dark" studies in NH infants, and here, we presented the first results from 6 children with BiCIs and 13 NH children.

Results suggest that the RFS method is successful in distinguishing between performance of the BiCI users when listening bilaterally versus unilaterally. Although all 6 children reached criterion for all locations tested, their ability to perform the task when listening through a single CI was notably worse. This finding is consistent with the recent results on MAA in 2.5-year-olds, in which bilateral benefits for spatial hearing were observed: children who were able to perform the task with BiCIs were generally unable to perform the task when using a single CI (10,14). Similar findings were observed with the MAA task in older children (8,15) and also on measures of sound localization (4).

In the present study, there was notable variability on how well the children were able to perform the task in the

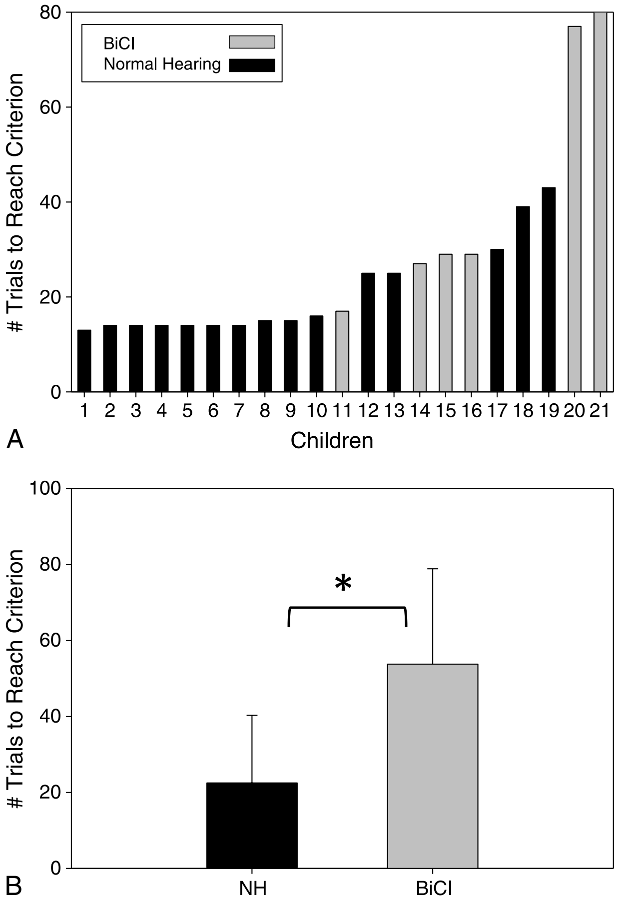

FIG. 3. Number of trials to reach criterion are shown for individual children (panel *A*) and for the 2 groups (±SD). In panel A, the data from children with normal hearing (NH) and with BiCIs are rank-ordered by number of trials regardless of which group the children were in. Children with NH and BiCIs are shown in *dark and gray bars*, respectively.

unilateral listening mode; some were unable to at any of the locations, and others were able to perform the task at the larger or intermediate angles. This finding suggests that, although the monaural listening condition is not one that the children encounter in their everyday listening, some children were able to use overall monaural and spectral cues to discriminate sounds arriving from the right versus left. In this testing situation, children were less than 1 m from the loudspeakers, thus in the near field, where overall level cues can be robust.

The RFS method was also successful in eliciting NH-like percent correct outcomes from all 6 BICI users, when these children listened through their bilateral devices. Although the N size is relatively small in this study, the fact that all children were consistent in being able to discriminate the smallest angles tested (±15 degrees) suggests that this approach provides the desired ecologically motivating task for this age group, which is generally difficult to engage on perceptual tests for long periods. The RFS method used here also revealed interesting differences between the NH and BiCI groups regarding the task difficulty or attention on the task. This difference became apparent when comparisons between groups were made on the number of trials to reach criterion, and the number of trials that were considered invalid and thus had to be repeated. Children with BiCIs required a greater number of trials to reach criterion, which directly reflects the number of invalid trials. This further performance assessment suggests that, although they were as accurate on the trials on which they produced a reach, there may have been other factors that resulted in BiCI users experiencing greater difficulty on the task. It is possible that, having had less exposure to auditory input, the BiCI users are less sure of what they perceive and take longer to get trained, and they may also continue to hesitate throughout the testing session. Recent studies in children who use CIs suggest that, on measures of short-term working memory capacity and verbal rehearsal speed, children with CIs were delayed relative to NH peers (16). These delays may account for some of the differences observed on tasks of spatial hearing. BiCI users are known to receive degraded binaural signals and thus have spatial hearing maps that are poorly defined

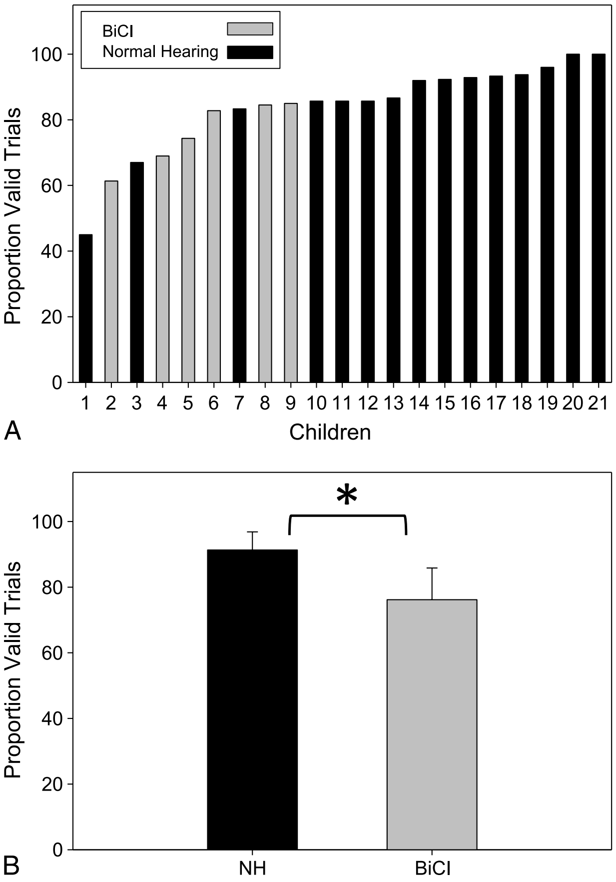

FIG. 4. Proportion of trials tested that were considered to be valid are shown for individual children (panel *A*) and for the 2 groups (±SD, panel *B*). In panel A, the data from children with normal hearing (NH) and with BiCIs are rank-ordered by number of trials regardless of which group the children were in. Children with NH and BiCIs are shown in dark and gray bars, respectively.

(1–3). As a result, they are more tentative, perhaps less confident in their perception, in particular on novel tasks such as the one used in the present study. A recent study in our lab with the same age group may shed light on this result: word identification measures using the "looking while listening" paradigm showed that, compared with NH peers, BiCI users were slower to find a visual target matching an auditory stimulus (17). These findings may have implications for rehabilitation and underscores the importance of training at this young age.

Finally, it is important to consider the fact that this study examined discrimination of source locations (left versus right) using a 2-alternative forced choice task on each trial. Is it important to follow up this finding with measures of spatial hearing per se, that is, to understand whether the children who use BiCIs are able to identify source locations in a multi-loudspeaker array. Recent studies with children who have BiCIs who are older suggest that, although MAAs can be relatively small in many children, the ability to discriminate left-versus-right does not predict sound localization errors. More specifically, many children who have small MAAs have large root-mean-square errors, and close examination of the error patterns suggest that, although they can discriminate between the right and left hemifields, they have difficulty discriminating between source locations within a hemifield. This finding suggests that in many of the children studied to date, perceptual mapping of space is still emerging (4). By studying children who receive the second CI by age 18 months, we can begin to understand whether bilateral activation at the younger ages promotes faster emergence of perceptual mapping of space. This will be the topic of future work using the RFS methodology.

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