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Experience With Bilateral Cochlear Implants Improves Sound Localization Acuity in Children

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Hypothesis: Because of auditory plasticity, there can be experience-dependent acquisition and refinement of spatial hearing skills.
Background: A growing number of children who are deaf are receiving bilateral cochlear implants (CIs), in an attempt to provide them with acoustic cues known to be important for spatial hearing. A feasible and reliable task for children is the right-left discrimination task, which enables measurement of the smallest angle from midline that can be reliably discriminated (minimum audible angle [MAA]).
Methods: Ten children (5–10 yr of age) were followed longitudinally during their transition from 1 to 2 CIs, with testing before bilateral activation, as well as 3 and 12 months after bilateral activation. Testing at 3 and 12 months after bilateral activation was conducted under bilateral and first CI listening modes. During testing, stimuli were presented from an array of loudspeakers. On each trial, the child reported whether the sound was to the right or left, with feedback. Percent correct was measured in blocks of trials for numerous angle values.
Results: At baseline, some children were unable to perform the right-versus-left task, but group mean MAA was 44.8 degrees. MAA in the bilateral listening mode improved to 20.4 degrees at 3 months and 16.8 degrees at 12 months after bilateral activation. No improvement was seen in the unilateral listening mode. Bilateral performance was better than unilateral.
Conclusion: Spatial hearing skills in sequentially implanted children develop in an experience-dependent manner, perhaps because of the ability of the auditory system to use newly acquired electrical stimulation presented to the 2 ears. **Key Words:** Bilateral—Binaural—Children—Cochlear implant—Localization.
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A growing number of children who are deaf are receiving bilateral cochlear implants (CIs), in an attempt to provide them with acoustic cues that are known to be important for spatial hearing. The benefits of bilateral CI (BICI) in adults are well documented. When both CIs are activated compared with when a single CI is used, there seem to be significant improvements in the ability of adult patients to understand speech in noise (e.g., van Hoesel [1], Schleich et al. [2], Litovsky et al. [3]) and localize sounds (e.g., Nopp et al. [4] and Litovsky et al. [5]). The ability to identify source locations is the topic of interest in this study, with a particular focus on the minimum audible angle (MAA), that is, a left versus right discrimination task that aims to measure the smallest angle from midline that can be reliably discriminated (6–8). We have previously reported that MAA thresholds in children with BICIs are significantly smaller when bilateral devices are used than with the CI in the first implanted ear (9). In a few of these children, we also documented the finding that MAA thresholds improved over time. Although bilateral implantation has become more common in children in recent years, many clinical questions arise, such as whether simultaneous or sequential implantation might offer similar outcomes. Children who are implanted sequentially experience several changes in auditory input during childhood because they typically transition from being bilaterally deaf to being unilaterally implanted and then bilaterally implanted. In addition, some children are fitted with a hearing aid in the nonimplanted ear, thus they transition from having bimodal (acoustic + electric) hearing to having bilateral electric hearing. Other children transition from being unilaterally implanted with no input in the contralateral ear to having bilateral electric hearing. This study was concerned with the emergence of spatial hearing abilities in a group of children who experienced

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these transitions. The study was prospectively designed to capture MAA thresholds while the children were unilateral CI users and at 2 subsequent intervals after activation of the second CI: 3 and 12 months. We tested the hypothesis that, because of auditory plasticity, that is, the ability of the auditory system to integrate novel stimulation from the 2 ears, there can be experience-dependent acquisition and refinement of spatial hearing skills. Change in performance over time was tracked for both unilateral and bilateral listening modes. Because the same group of children was tested before and after activation of the second CI, they served as their own unilateral control.

MATERIALS AND METHODS

Subjects

Ten children (5–10 yr of age) were followed longitudinally during their transition from 1 to 2 CIs. Upon enrollment in the study (i.e., baseline visit), each of the children had at least 1 year of experience with a single CI, used oral communication, and was mainstreamed in his/her school setting. Six of the children wore a hearing aid in the ear contralateral to their CI during waking hours (CI-HA). The other 4 children received no consistent stimulation to the contralateral ear (UniCI). At the baseline visit, testing was completed in either CI-HA or UniCI listening mode, depending on the child. After activation of the second CI, the children returned for further participation, after having had 3 and then 12 months of listening experience with bilateral CIs. Because of logistical issues, 1 subject, CIAY, participated at 3- and 9-month intervals. Demographic information is presented in the Table.

Implant Devices

The children were recruited from a wide array of geographic locations and CI centers across the United States. The device manufacturer was not a controlled variable in this study. Device types for each child are listed in the Table. Because of the sequential nature of the operations and device manufacturer upgrades, 7 of the 10 children received a newer internal device model (electrode array and receiver) for their second CI as compared with their first CI. Device programming was completed by each child's audiologist during regularly scheduled appointments. In most cases, device programming was done independently for each ear, as was customary in those clinics. The program most often used in daily listening situations, based on parent report and audiologist recommendation, was the one chosen for all aspects of research participation. On the first day of study participation, volume control and/or sensitivity were adjusted to equalize (as much as possible) the loudness perception produced by the 2 implants. The loudness balancing procedure used subjective report from the participant.

Testing Environment

Testing was conducted inside a standard Industrial Acoustics Company double-walled sound booth with inner dimensions of 2.8 × 3.25 m. During testing, the child was seated at a small foam-covered table, facing a semicircular arc. Frequency-matched loudspeakers (Cambridge SoundWorks, Center/Surround IV, North Andover, MA, USA) were mounted at ear level and were positioned along the arc at 10-degree intervals

TABLE. *Subject characteristics*

	Subject	Sex	Etiology	Age at first CI activation Yr;Mo	Age at second CI activation Yr;Mo	Time between first and second CI Yr;Mo	Contralateral HA at baseline	First CI	Second CI
CI-HA at baseline	CIAP	F	Progressive, cause unknown	3;6	5;2	1;8	Oticon DigiFocusSP; left ear	Nucleus 24C Advance; right ear	Nucleus 24C Advance; left ear
	CIAQ	M	Connexin-26	3;1	8;1	5;0	Widex Senso P38; left ear	Nucleus 24C; right ear	Nucleus 24C Advance; left ear
	CIBA	M	Connexin-26	3;7	10;2	6;7	Phonak Supero 412; right ear	Nucleus 24; left ear	Nucleus Freedom; right ear
	CIBH	M	Mondini Malformation	2;5	7;0	4;7	Phonak P4AZ; right ear	Med-El Combi40+; left ear	Med-El Pulsar; right ear
	CIBK	M	Connexin-26	2;1	7;1	5;0	Oticon DigiFocus II; left ear	Nucleus 24C; right ear	Nucleus Freedom; left ear
	CIBM	M	Progressive, viral cause suspected	3;9	8;0	4;1	Sonic Innovations Digital BTE; right ear	Nucleus 24; left ear	Nucleus Freedom; right ear
UniCI at baseline	CIAW	M	Prenatal CMV exposure	1;2	5;5	4;3	NA	Nucleus 24C; right ear	Nucleus Freedom; left ear
	CIAY	M	Progressive, bilateral ear infection	5;2	5;11	0;9	NA	Nucleus 24C Advance; right ear	Nucleus 24C Advance; left ear
	CIBG	M	Unknown	1;2	5;5	3;3	NA	Nucleus 24; right ear	Nucleus Freedom; left ear
	CIBJ	F	Progressive, cause unknown	3;9	8;0	4;1	NA	Advanced Bionics CII/HiFocus; left ear	Advanced Bionics HiRes/90K; right ear

CI indicates cochlear implant; CI-HA, subjects who wore hearing aid in the ear contralateral to their cochlear implant; F, female; M, male; UniCI, subjects who received no consistent stimulation to the contralateral ear; CMV, Cytomegalovirus; NA, none.

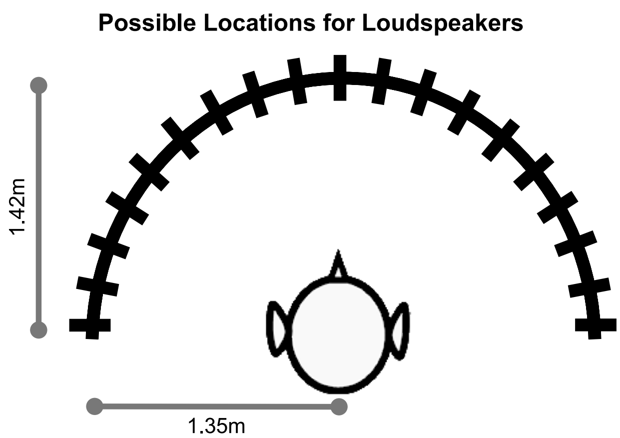

FIG. 1. Testing apparatus for MAA included loudspeakers placed at 10-degree increments from −90 to 90 degrees. The child's head was always 1.42 m from the 0-degree loudspeaker and 1.35 m from the loudspeakers at −90 and 90 degrees.

ranging from −90 to 90 degrees. The child's head was always 1.42 m from the 0-degree loudspeaker (Fig. 1). The children were instructed to face and look at the computer monitor positioned underneath the center loudspeaker and to refrain from moving their heads during stimulus presentation.

The stimulus used was the spondee "baseball" recorded using a male voice at a sampling rate of 44,000 Hz and digitized as a .wav file. Stimuli were amplified and sent to the loudspeakers via Tucker Davis Technologies System III hardware with a PC host. Stimulus levels were set to an average level of 60 dB sound pressure level (SPL), with random roving between 56 and 64 dB SPL (i.e., ±4 dB), to minimize monaural level cues. The reader is referred to Litovsky et al. (9) for a discussion of the use of this spondaic stimulus for this task. Testing was conducted through a computer "listening game" platform whereby the child was presented with response options via a computer monitor and mouse. The computer monitor was positioned underneath the front loudspeaker at 0 degrees to avoid interference with the stimuli as they arrived at the ears; the mouse was placed on the small table in front of the child. A trained tester was present in the sound booth at all times. During testing, feedback was provided through flashing icons presented by the computer. In addition, reinforcement was provided on a trial-by-trial basis using computerized puzzle pictures revealed 1 piece at a time. Stickers and prizes were awarded between test measures as further reinforcement.

Psychophysical Measurement

Testing was conducted using a 2-alternative forced choice procedure. On each trial, the stimulus was presented from a loudspeaker to the child's left or right. The child indicated a response either using the computer mouse or by pointing to the right/left hemifield. After each response, feedback was provided whereby the correct hemifield was revealed to the child via a blinking response icon on the computer monitor. Testing was conducted in blocks of 20 trials, during which a pair of loudspeakers on the arc that were equidistant from the center were selected and labeled with icons matching the computer response icons. The angular separation of the loudspeakers from the center was varied between trial blocks using a modified adaptive rule based on the child's performance (see Litovsky et al. [9]). Testing was initiated with angles ranging from 40 to 90 degrees from center, with exact angle guided by pilot testing or previous data obtained with the child. Following blocks in which the child obtained 75% or greater correct, angle size was decreased; otherwise, the angle size was increased. Decreases in angle size were initially in steps of 20 degrees, with smaller increments (smallest being 2.5 degrees) used on successive blocks of trials. Testing was terminated when testing with a successive pair of angular separations yielded performance of 75% or greater correct and less than 70% correct. Psychometric functions were extracted from the data, and MAA threshold was estimated by finding the smallest angular separation on the psychometric function where performance yielded 72.4% correct (i.e., 2 standard deviations above chance performance).

At the baseline visit, participants completed MAA testing in either the CI-HA or UniCI listening mode. In subsequent visits, participants completed MAA testing while in BICI and UniCI (with only the first CI turned on) listening modes. During the baseline visit and the 3-month bilateral visit, children underwent training on the task using a fixed stimulus presentation level of 60 dB SPL. If they were able to perform the task at large angle separations with the criterion of 75% or greater, they were subsequently tested with overall sound level varying randomly from 56 to 64 dB SPL to minimize monaural level cues. Three children (CIAP, CIAW, and CIBG) experienced difficulty with the task and were therefore not tested on additional conditions in which the level was roved during either the baseline or 3-month visit.

RESULTS

Figure 2 shows individual MAA thresholds for the 3 testing intervals (baseline, 3 and 12 months), in the BICI listening mode. During the baseline testing interval, some children were able to identify the correct hemifield with

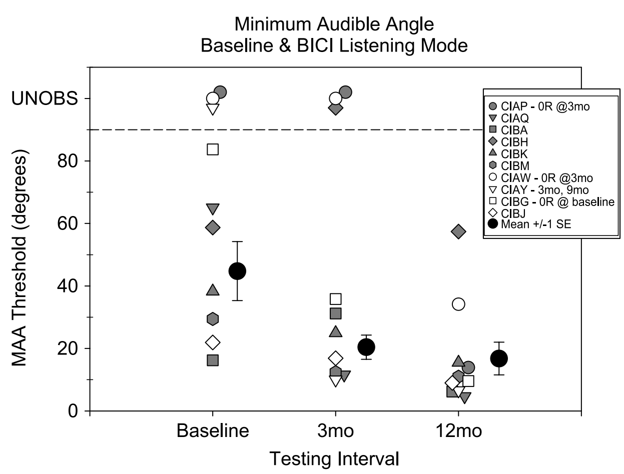

FIG. 2. Individual and group mean MAA are shown for baseline (CI-HA or UniCI) and for the BICI listening mode at 3- and 12-month test intervals. *Filled symbols* indicate participants who were tested in CI-HA listening mode at baseline; *unfilled symbols* indicate participants tested in UniCI listening mode at baseline. Means for each interval were computed using only data from participants whose results were measureable at that interval. Number of unobserved data points at each interval was as follows: baseline = 3, 3 months = 3, and 12 months = 0.

greater than 75% accuracy with no training. Other children had greater difficulty with the task and underwent several practice blocks at wide angular displacements (>60 degrees). Following practice blocks, 7 children were able to perform the task with greater than 75% accuracy on wide angle separation blocks, whereas 3 children were unable to perform the task, even at the widest separation of ±90 degrees (CIAP, CIAW, and CIBG). MAA threshold for these participants at the baseline interval, therefore, was considered unobserved data in the statistical analysis. In Figure 2, unobserved data points are denoted by the *y* axis label UNOBS. The number of children with observed data was 7 at baseline, 7 at 3 months, and 10 at 12 months.

As is shown in Figure 2, baseline thresholds are highly variable among the 10 subjects, ranging from 16.2 to 83.7 degrees for the 7 children who were able to complete the task. Variability decreased at the 3- and 12-month test intervals, as is evident from the error bars and spread in the data. By the 12-month interval, all participants were able to perform the task at 1 or more angles at a level of performance greater than 75% correct. In addition, at 12 months, all but 2 children achieved MAA thresholds of 15 degrees or smaller. Group means, (±1 standard error [SE]) plotted beside the individual data, were calculated at each testing interval based only on data from participants who were able to complete the task (no unobserved data). Average MAA thresholds decreased steadily during the intervals tested, from 44.8 degrees at baseline to 20.4 degrees at 3 months and finally to 16.8 degrees at 12 months.

It is interesting to note that the rate and pattern of improvement on the task varied by individual. As was previously mentioned, at baseline, performance ranged from 16.2 degrees to unobserved for the 10 participants and was not predicted by whether the participants entered the study with CI-HA or UniCI listening experience. At the 3-month visit, although most of the participants showed improvements in MAA threshold, 3 of the 6 children who entered with CI-HA listening experience (CIAP, CIBH, and CIBA) showed no change or a decrement in performance. By the 12-month visit, the decrement measured early on seems to have resolved. Furthermore, all but one participant (CIBH) showed gains in performance compared with baseline. It is possible that these children experienced a period of adjustment to bilateral electrical stimulation after bimodal (acoustic + electrical) stimulation that results in performance decrements during the initial months after activation of the second CI.

In Figure 3, group averages from Figure 2 (BICI listening mode) are replotted for comparison with data from the same children collected in the UniCI listening mode, at the 3- and 12-month intervals, along with the baseline data. Group averages for each listening mode at each test interval were computed using only data from participants whose results were measurable at that interval. For UniCI mode, the number of data points was 4 at 3 months and 9 at 12 months. Compared with the average MAA at baseline of 44.8 degrees, average UniCI MAA thresholds remained

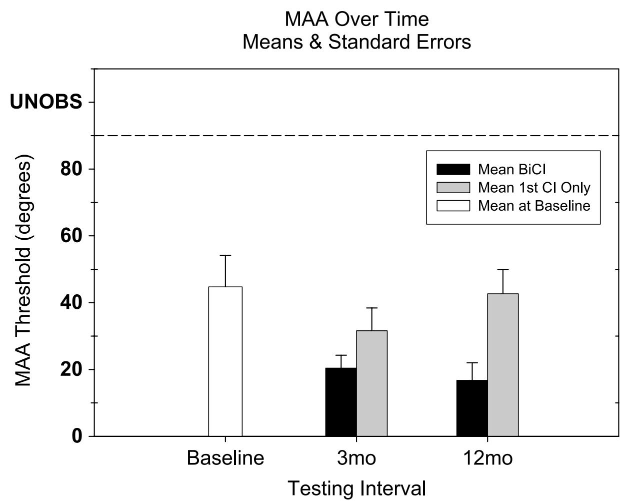

FIG. 3. Mean MAA for all participants at each of the 3 testing intervals. At baseline, 6 children were tested with CI-HA, and 4 children were tested with UniCI only. At the 3- and 12-month intervals, all children were tested both with BICI and UniCI (first CI only). Group means were computed using only data from participants whose results were measureable at that interval. Number of unobserved data points at each interval was as follows: baseline = 3, 3 months = 3(BICI) 6(UniCI), and 12 months = 0(BICI) 1(UniCI).

high after activation of the second CI: 31.6 degrees at 3 months and 42.7 degrees at 12 months.

Because of the unobserved data points contained in the dataset, standard statistical methods could not be used. To evaluate the differences in gains between the BICI and UniCI modes from baseline to 12 months, a random coefficient model was fit to the data from 10 subjects with respect to a baseline condition (common to both CI-HA and UniCI modes) and both UniCI and BICI modes at 3 and 12 months. The angular outcome measure was log-transformed to achieve approximate normality and homogeneity of variance across listening modes. The random coefficient model used in the current analysis characterized individual differences in reference to 3 parameters—an intercept (representing expected score a baseline), a linear slope related to the UniCI mode, and a linear slope related to the BICI mode. The 2 linear slopes represent expected gains (per month) with respect to log-angular measure under the UniCI and BICI modes, respectively. We tested the hypothesis that the mean difference in slopes between the BICI and UniCI modes would be negative, implying greater gains in the BICI mode. We compared 2 nested models: 1) a baseline model in which the difference in the mean slopes across BICI and UniCI modes is allowed to be nonzero and 2) a comparison model in which the difference in the mean slopes is constrained to be 0. In both models, the residual variances associated with each of the 5 repeated measures (baseline, UniCI at 3 months, UniCI at 12 months, BICI at 3 months, and BICI at 12 months) are constrained to be equal.

Both the baseline and comparison models were fit using Mplus, version 4 (10) and compared using a χ^2 difference test. Data points that were unobserved because of the subject not being able to complete the task were treated as censored from above. Mplus uses a weighted least squares missing value estimator for both models.

The model fit observed for the baseline model was quite good (χ^2_4 = 1.854, p = 0.763; CFI = 1.00; TLI = 1.01; Root Mean Square Error of Approximation = 0.000; Weighted Root Mean Square Residual = 0.414). The results of the χ^2 difference test comparing the baseline and comparison models was significant (χ^2_1 = 12.323, $p < 0.001$), implying a significant mean difference in the slopes between the UniCI and BICI modes. From the baseline model, the mean slope for the UniCI mode (−0.031, SE = 0.020, t = −1.525, not significant) is significantly above that for the BICI mode (−0.138, SE = 0.028, t = −4.989, $p < 0.01$), suggesting significantly greater improvement for the BICI mode. Moreover, the pattern of statistical significance for the individual parameter estimates implies no detectable gains under the UniCI mode but detectable gains under the BICI mode.

To further investigate the presence of differences in the UniCI and BICI modes at both 3 and 12 months, a random coefficient model was specified in which all measures were associated with a common slope, but the intercepts associated with the BICI mode measures at 3 and 12 months were allowed to be nonzero. In this way, we can test whether the mean scores observed at these time points for the BICI mode differ from those expected under the UniCI mode. The intercept for the BICI mode was estimated at −0.499 (SE = 0.562, t = −0.877, not significant) at 3 months and at −1.270 (SE = 0.349, t = −3.645, $p < 0.01$) at 12 months. Thus, significantly better scores were only detected at the 12-month time point under the BICI mode, suggesting that after 1 year of bilateral experience, spatial hearing improves significantly in the BICI mode.

DISCUSSION

The purpose of this study was to evaluate the emergence of spatial hearing skills in sequentially implanted children and to test the hypothesis that because of auditory plasticity, there can be experience-dependent acquisition and refinement of spatial hearing skills. This work was motivated by the fact that, clinically, the number of children who are receiving BICIs is growing, yet little is known about the extent to which sequential versus simultaneous implantation and activation of the devices will impact outcomes. By testing children who are 5 to 10 years of age, we were able to focus on the issue of early binaural deprivation and to look at its impact on spatial hearing.

Results showed that children performed better when listening with both CIs than unilaterally. In addition, at baseline, that is, with the use of a single CI and either an HA in the other ear or no stimulation in the other ear, performance was generally poorest. Group mean MAAs improved somewhat by 3 months, but statistically significant improvement in the BICI condition was noted at 12 months after bilateral activation. These results suggest that nearly all children tested here, who received the second CI between the ages of 5 to 10 years, were able to perform better on a measure of sound localization acuity after 1 year of listening with both of their devices. Some of the children experienced progressive hearing loss; thus, they may have had exposure to binaural acoustic hearing before becoming deaf. However, other children with Connexin-26 had profound hearing loss from birth and had experienced up to 10 years of auditory deprivation in the second implanted ear. Subjects CIBA, CIAQ, and CIBK had bilateral auditory deprivation until ages 3;7, 3;1, and 2;1, respectively. They then remained unilaterally implanted until ages 10;2, 8;1, and 7;1, respectively. Nonetheless, their MAA thresholds at the 12-month interval were 6.2, 4.7, and 15.5 degrees, all at or below the average MAA for the 12-month interval. This finding supports the notion that the auditory system of children who are born deaf and do not receive bilateral hearing for a number of years is highly capable of processing spatial cues relevant for sound location discrimination. Evidence for auditory plasticity exists in other species (11–13) and lends support to the notion that bilateral implantation may have a protracted window of opportunity for emergence of spatial hearing benefits. What remains unclear is whether these children would perform just as well as their peers with earlier onset of bilateral activation on other important measures, such as sound localization in more challenging tasks, speech-in-noise, language and speech acquisition, as well as nonauditory abilities. It has been shown, for example, that the age at which the second CI is activated can have significant effects on speech perception in quiet and in noise. Peters et al. (14) demonstrated that children who receive a second CI by age 3 to 5 years are more likely to have speech scores in the second implanted ear that catch up to speech scores in the first implanted ear than children whose second CI is activated at ages 5 to 8 years and more so compared with activation at age 8 to 13 years.

A further observation regarding the baseline condition applies to a unilateral child without a HA who was most likely able to use subtle monaural level cues (CIBJ) to perform the task, and several children with an HA in the nonimplanted ear, who were likely able to extract binaural cues from bimodal stimulation (CIBA, CIBK, and CIBM). Although they all improved from baseline to 12 months, the amount of improvement that could be measured for these "better initial performers" was limited by a floor effect with the MAA task. A more rigorous measure of spatial hearing, such as sound localization in a multi-loudspeaker listening situation, would be required to determine the extent to which this cohort of children also may have benefited from bilateral implantation.

It is further important to note that the improvement on the MAA task documented here was seen in the bilateral listening mode; however, there was no improvement when testing was done in the unilateral listening mode.

One might argue that testing these children with a single CI once they have been bilaterally implanted creates a disadvantage in the unilateral listening mode because the children are no longer accustomed to using a single CI in their daily lives. Nonetheless, given that they had numerous years of use with that single CI before being bilaterally activated, the unilateral testing mode provides an opportunity for examining overall change in performance.

One child (CIBH) did not show improvement from baseline to 12 months. As can be seen from the participant characteristics in the Table, the factors that contributed to lack of improvement in this child's performance are not easily identifiable, other than him being the only child with mondini malformation. Otherwise, this child had a similar age at first implantation and similar amount of delay between activation of the 2 CIs to other participants who did show improvement. Thus, it may be the case that, with additional bilateral experience, this child would have caught up with the other participants and shown improvement on the MAA task, as has previously been shown (9). Although this child wore a contralateral hearing aid until the time of second CI surgery, he may still have suffered from auditory deprivation in the second-implanted ear due to lack of usable hearing. Future work with a larger population of children who meet these recruitment criteria may be necessary for understanding the factors that contribute to this finding.

In conclusion, spatial hearing skills as measured with a right-left discrimination task emerge in sequentially implanted children in an experience-dependent manner, perhaps because of the ability of the auditory system to use newly acquired electrical stimulation presented to the 2 ears.

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