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Bilateral cochlear implants in children: Effects of auditory experience and deprivation on auditory perception

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Abstract

Spatial hearing skills are essential for children as they grow, learn and play. They provide critical cues for determining the locations of sources in the environment, and enable segregation of important sources, such as speech, from background maskers or interferers. Spatial hearing depends on availability of monaural cues and binaural cues. The latter result from integration of inputs arriving at the two ears from sounds that vary in location. The binaural system has exquisite mechanisms for capturing differences between the ears in both time of arrival and intensity. The major cues that are thus referred to as being vital for binaural hearing are: interaural differences in time (ITDs) and interaural differences in levels (ILDs). In children with normal hearing (NH), spatial hearing abilities are fairly well developed by age 4–5 years. In contrast, children who are deaf and hear through cochlear implants (CIs) do not have an opportunity to experience normal, binaural acoustic hearing early in life. These children may function by having to utilize auditory cues that are degraded with regard to numerous stimulus features. In recent years there has been a notable increase in the number of children receiving bilateral CIs, and evidence suggests that while having two CIs helps them function better than when listening through a single CI, they generally perform worse than their NH peers. This paper reviews some of the recent work on bilaterally implanted children. The focus is on measures of spatial hearing, including sound localization, release from masking for speech understanding in noise and binaural sensitivity using research processors. Data from behavioral and electrophysiological studies are included, with a focus on the recent work of the authors and their collaborators. The effects of auditory plasticity and deprivation on the emergence of binaural and spatial hearing are discussed along with evidence for reorganized processing from both behavioral and electrophysiological studies. The consequences of both unilateral and bilateral auditory deprivation during development suggest that the relevant set of issues is highly complex with regard to successes and the limitations experienced by children receiving bilateral cochlear implants.

II. INTRODUCTION

As they grow, children are faced with increasing demands to function in complex listening environments, to integrate into mainstreamed educational and social situations, and to

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engage effectively and productively in a multi-sensory world. Spatial hearing skills are amongst the most important for maximizing these abilities, by providing critical cues for determining the locations of sources in the environment, and enabling segregation of important sources such as speech from background maskers or interferers. A child's ability to take advantage of these cues is likely to facilitate functioning in numerous everyday environments, enhancing incidental learning, and reducing fatigue and cognitive load.

It is well known that spatial hearing relies to some extent on monaural cues, but more importantly, good spatial hearing requires that the auditory system be able to integrate inputs arriving at the two ears from sound sources that vary in location in space. This "binaural integration" has exquisite mechanisms for capturing differences between the ears in time of arrival and intensity. One major cue thought to be vital for binaural hearing is the interaural difference in time (ITD), or difference between the ears in time of arrival of the sound. ITD cues in humans are equal to zero for sounds arriving from directly in front, and as sources are displaced laterally, ITDs grow more or less linearly until they reach a maximum value of approximately 700 μs for an average adult size head. A second major cue is the interaural difference in level (ILD). This cue, which is equal to zero when stimuli arrive from directly in front, increases as stimuli are displaced laterally. ILDs result from 'shadowing' of the stimulus level at each ear, depend on the frequency of the sound being produced, such that the largest ILDs (~20 dB) occur at high frequencies. In addition, high frequency stimuli with amplitude modulations can contain ITD cues, and NH listeners show excellent sensitivity to such ITDs. CI speech processors are typically programmed with high-rate pulsatile stimulation; these rates are higher than the rates at which ITD sensitivity is observed. Thus, it is possible that envelope ITDs would be usable for spatial hearing abilities in CI users. However, the issue has not been studied in detail, an in fact data from NH listeners suggest that envelope ITDs have not been demonstrated to be effective for localization judgements [1]

In normally developing hearing systems, ITDs and ILDs are initially processed at the level of the auditory brainstem, and are continually refined and mediated by excitatory and inhibitory neuronal mechanisms that ultimately enable the brain the determine locations of sources in space. Excellent reviews on this topic are available for more detailed explanations and examples [2–4].

In children with normal hearing (NH), spatial hearing abilities are fairly well developed by age 4–5 years [5] [6]. However, it is likely that the ability to achieve good level of functioning regarding spatial hearing depends on the child's access to normal acoustic cues. By contrast, children who are deaf and hear through CIs do not have an opportunity to experience normal, binaural acoustic hearing early in life, and they function by having to utilize auditory cues that are degraded when it comes to numerous stimulus features (for review see [7, 8]). When considering children who are bilaterally implanted, it is important to understand the extent to which maturation of spatial hearing depends on, and can vary with, exposure to bilateral stimulation. In addition, it is important to consider the potential role of experience on children's ability to utilize spatial information. For example, it is possible that binaural cues are weak or subtle, such that children require experience with them in order to learn to utilize them. However, if spatial cues are not preserved with fidelity by the CI processors, then regardless of how much experience children have, they may never improve in their spatial hearing abilities. Additional studies are also discussed here, whereby the CI speech processors are bypassed, and research processors are used in order to provide binaural cues to specific pairs of electrodes in the two ears. Both behavioral and electrophysiological data are discussed here, to consider how place of stimulation as well level and timing of bilateral implant stimulation may affect spatial hearing in children. Finally, investigations of developmental plasticity after implantation are reviewed in an effort to explore both the successes and the limitations experienced by children receiving bilateral cochlear implants.

III. SPATIAL HEARING IN BILATERALLY IMPLANTED CHILDREN

In the past 10–15 years there has been a progressive increase in the number of children receiving bilateral CIs, with growing evidence that, when listening with two CIs children generally perform better on spatial hearing tasks compared with unilateral listening modes. However, as is reviewed here, even with years of experience with bilateral CIs, most children do not perform as well as their NH peers.

A common measure of spatial hearing is sound localization. This ability has been studied using one of two approaches. First, localization acuity is a measure of how well a listener can discriminate between two source locations; often this measure is obtained for locations to the left vs. right, and the smallest angular difference between the two locations is a measure of acuity. A common metric is the minimum audible angle (MAA) [9, 10]. For recent reviews on this topic see also [5, 6]. A second measure is localization accuracy, which is informative regarding the ability of a listener to identify the location of a sound source from amongst an array of sources; accuracy can be measured for sound sources along the vertical or horizontal dimension but in bilateral CI users the focus has been on the horizontal plane, where binaural cues would be most effectively utilized [11]. Figure 1 summarizes data from recent studies in which acuity and accuracy were measured in children with bilateral CIs. Of interest in these studies is the age of the children, task used and the amount of bilateral experience, which are summarized for panels 1A and 1B in Tables 1A and 1B, respectively.

As can be seen in Figure 1, sound localization abilities of children with bilateral CIs have a number of important characteristics. First, the ability to discriminate sound sources, i.e., the MAA and other right-left discrimination measures, reveal a spatial hearing system that is fairly well established in a portion of the population. Some children as young as 2–3 years of age are able to discriminate left vs. right at small angles, with many children showing results that are within the range of what is seen in NH age-matched peers. However, there are also children who do not reach the performance level of age-matched peers and the reasons for this poor performance have not been fully identified (see further discussion below).

On the sound localization task, performance varies substantially across subjects, and it is possible that localization undergoes a more protracted developmental time course. Children who can typically perform the MAA task are not able to identify sound source locations well. While some of the children have error rates that are fairly low, none are as 6 low as typically developing NH children. Figure 2 shows examples of data from children between 5 and 14 years of age who received sequential bilateral CIs, and 5-year old children with NH. The best performing children with bilateral CIs have error rates within the range seen in the NH group. In the bilateral CI group, spatial hearing skills appear to be represented through different types of localization strategies that, with experience, undergo transitions from more rudimentary sound source categorization to more fine-grained ability to identify source locations. However, even after >4 years of bilateral experience children with bilateral CIs continue to show errors that are generally higher than the average age-matched NH peers [11]. Little work has been done to date on the impact of auditory training, but it is possible that localization abilities would be further improved by training in a spatial hearing task.

Overall the data also show that the bilaterally implanted children do not reach the same level of performance as their age-matched NH peers. In fact, even the bilateral CI users who have had >6 years of experience listening with their CIs did not perform as well as the children with NH. There are numerous factors that might account for the gap in performance between children with bilateral CIs and NH children: (1) When clinical processors are used and sounds are presented to the children from loudspeakers in a sound field, there is no coordinated activation of the two speech processors. (2) CI processors do not deliver temporal fine structure cues that are important for spatial hearing using low frequency sounds. (3) It is possible that there are anatomical mis-matches between the depth of insertion of electrodes in the right and left ears. This might create a mis-match in the frequency representation of signals presented to electrodes along the arrays in the two ears that are anatomically parallel. This could minimize the ability of the binaural circuits to integrate inputs from the two ears and compute source locations. These factors are also discussed in relation to adults with bilateral CIs in a recent review [8]. Effects of asymmetric hearing during development may also be relevant as discussed further below.

A second measure of spatial hearing is known as “spatial release from masking” (SRM), which refers to the improvement in speech understanding in the presence of interfering sounds, also known as maskers. Testing is conducted when the target speech and maskers are spatially separated vs. when they are co-located. This improvement can either be measured by comparing changes in percent correct for speech understanding, or by measuring differences in speech awareness or reception thresholds for separated vs. co-located conditions. Figure 3 shows a schematic of conditions used to test for the SRM effect. In the co-located condition, the target and maskers are presented from the front, and signals at the two ears have the time arrival intensity. In the asymmetrically separated condition, the target in front but the maskers are presented from one side, thus the ear farther from the masker has a reduced overall level relative to the ear that is near the masker. The target thus has a good signal-to-noise ratio (SNR) in the ear that is far from the masker (left ear in this rendition) compared with the ear near the masker. This ‘better ear effect’ enables listeners to rely on monaural head shadow cues for extracting information from the target speech. By contrast, in the symmetrically separated condition, having maskers on both sides of the head renders neither ear in a position of having a good SNR. In this case, listeners do not have monaural head shadow cues, and must rely on binaural processing for source segregation.

Figure 4 shows recently published data [12] in which these conditions were studied and results are compared for the bilateral CI users and NH children as well as NH adults.

Results suggest that NH children had SRM in both conditions; however, the effect was larger in the asymmetrical condition. Thus, having access to normal acoustic cues renders children able to use binaural cues for source segregation when monaural head shadow cues are minimal or absent. In addition, the monaural head shadow cues do provide an added benefit for NH children. In the CI groups SRM was small or even negative in the symmetrical conditions, and measurable, but smaller than that of NH children in the asymmetrical conditions. This findings suggested that children who use bilateral CI rely on the ear with a better SNR, however, binaural mechanisms involved in SRM are weak or absent in these children. Results from a study by Van Deun and colleagues [13] are consistent with this observation; bilaterally implanted children demonstrated benefits due to head shadow effects around 4–6 dB, which was comparable to effects observed in NH children. However, effects due to binaural processing were not observed.

A second effect studied was related to target-masker similarity. It has been suggested that spatial cues become especially useful for source segregation when sources are highly similar or confusable [14]. Similarity and confusability between target and maskers can occur, for instance, when the sources consist of same-sex vs. different-sex talkers (e.g., [15]). SRM was larger in conditions with same sex talkers (i.e., in the top panel where both target and masker were male), a finding that is consistent with observations reported in NH adults [16].

The children with CIs had the same 'hearing age' as the NH children, suggesting that auditory experience is not sufficient for explaining why the gap in performance exists between bilaterally implanted children and NH children. Further evidence comes from data in NH children who show large SRM values by 3–5 years of age [17, 18]. Recently, Litovsky and Misurelli [12] found that when SRM is measured at annual intervals, the effects are not stable across the population of children with bilateral CIs: in some children SRM increased with additional listening experience, in other children the reverse was true, and in others there were no notable effects. Because test-retest data from a previous study showed that performance was stable [19], the changes denoted here were discussed in the context of other factors. For example, the authors speculated about the possible detrimental effects caused by signal processing in the microphones, about lack of bilateral mapping and hence asymmetries between frequency-allocation of speech signals in the two ears. They also discussed the possibility that children who use FM systems may become accustomed to listening to speech that has excellent SNR, and are therefore less adept at extracting information from target speech in the presence of maskers when the FM system is not available.

Asymmetric auditory development impairs speech unmasking. Children with simultaneous implantation of bilateral CIs benefited from moving noise away from speech by 90 degrees by 7.2 dB with no effect of the side of noise in measures of speech unmasking whereas a group of children who were sequentially implanted performed significantly better when noise was on the side of the second ear (4.8 dB) rather than the first ear (3.0 dB) [20]. The asymmetric findings in the sequentially implanted group were consistent with earlier reports

[21], showing weaker effects (< 1 dB) on speech detection thresholds when noise was moved to the side of the first CI in bilaterally implanted children and to the CI in children using a hearing aid in the other ear (bimodal users) than when noise was moved toward the poorer hearing/second implanted ear (~4 dB). Speech reception threshold data from Sparreboom and colleagues (2011) show a similarly small (1.8 dB) advantage of moving noise from the co-incident position with speech in front to the side of the first CI. Effects of moving noise to the opposite side of the head were not measured and thus asymmetry was not assessed in that study. More recently, Killan and colleagues [22] have shown that SRM measured with speech reception thresholds improves with ongoing bilateral implant use between 2–4 years following sequential cochlear implantation. This is consistent with the finding that SRM decreases with age in bilateral implant users [20]. Poorer benefits when noise was moved to the first than second implanted ear were found at 24 months of bilateral implant use (3.3 dB poorer). The asymmetry decreased but persisted at a follow-up of 48 months of bilateral use (1.8 dB asymmetry in SMR). In sum, the data indicate that children using bilateral cochlear implants obtain spatial benefits for listening to speech in noise but the advantages can be limited by asymmetric development and other mismatches between devices.

IV. DIRECT STIMULATION OF BINAURAL HEARING

Studies discussed thus far present stimuli from loudspeakers and allow the speech processors in the two ears to respond to the stimuli as they would in clinical situations. Because the two CIs are not coordinated, as described above, binaural cues are degraded, discarded or possibly occur in a spurious fashion. Studies using research processors provide an opportunity to directly stimulate select pairs of electrodes in the two ears, and the researcher can control many important parameters. Both behavioral and electrophysiological data in bilateral CI users reveal that the ability of CI users to integrate stimuli from the two depends on the place of stimulation along the cochlear implant electrode arrays, the level of the stimuli at each electrode and the relative timing of the signals. Most of the work on this topic to date has been conducted in groups of adult CI users [reviewed in [8, 23]. The current review focuses on what has been learned to date in children, and references the adult literature for comparison. Overall, findings with adults suggest that, despite tight control over binaural cues with research processors, finestructure ITD sensitivity is poorer than that seen in NH adults. More so, ITD sensitivity in CI users is best at very low pulse rates, and very poor at higher pulse rates, i.e., rates that are typically used in clinical speech processors.

Measures of binaural sensitivity in children with bilateral CIs reveal important differences from their NH peers. Litovsky and colleagues use identical paradigms to those established to date with the adult patients, except that the interactive computer tools are designed to engage the children in the tasks, reinforce them throughout the experimental procedures. In these studies, pulsatile stimulation is presented with varying rates and great effort is taken to find electrodes in the two ears that are matched by pitch and perceived loudness (e.g., [24, 25]).

One common perceptual measure of binaural sensitivity is discriminability for sounds that vary in either ITD or ILD. In a recent study, Litovsky and colleagues [26] used two types of stimuli to measure binaural sensitivity in 8–10 year old NH children. One stimulus was a transposed tone, which has high-rate carriers with amplitude modulations. The other was a CI simulation using a Gaussian Envelope Tone (GET) vocoder. In both cases, ITD cues are available in the envelope but not in the temporal fine structure. On average, NH children were able to discriminate ITDs and ILDs as well as adults, but there was more variability in the children than adults. ITD Thresholds in children ranged from 34–389μ and 15.6–362μ for the transposed and GET stimuli, respectively. In adults, thresholds ranged from 38–124μ and 27–356μ for the transposed and GET stimuli, respectively. ILD thresholds in children were 0.5–1.8 and 0.7–6 dB for transposed and GET stimuli, respectively. Finally, in adults ILD thresholds 0.5–1.8 and 0.5–6.7 dB, for the transposed and GET stimuli, respectively. Overall, those findings suggest that binaural sensitivity to ITDs in the envelopes is achievable by children ages 8–10 with NH, and that auditory development is unlikely to be the reason for poor performance in bilaterally implanted children.

In that same study, children's ability to perceptually locate sounds "in the head" (lateralization) was also measured, and results showed a markedly different level of performance in children vs. adults, suggesting that, although binaural acuity for these stimuli is well developed in early childhood, there is poor spatial mapping of those same cues. This finding has similarities to the results described above from the MAA and localization studies in free field, in that children with bilateral CIs are generally capable of discriminating source locations to the right vs. left, but they have a poorly established map of auditory space.

In general, it appears important to provide stimulation at places of stimulation that are matched because the bilateral pathways are tonotopically organized [27]. Yet, the most commonly used cochlear implant stimulation mode is monopolar where the current can spread over a range of several mm, stimulating large regions of the auditory nerve in each ear. Thus, it is not clear to what extent exact matching of stimulation across the ears by place and/or pitch perception is needed. Gordon and colleagues showed that children who are deaf retain tonotopic organization of bilateral pathways. In that study, the authors used an electrophysiological measure of the auditory brainstem called the binaural interaction component (BIC) or binaural difference (BD) [28]. This measure, also used to match electrodes in bilaterally implanted cats [29] and adult users [30, 31], produces a difference between the sum of brainstem responses to each implant separately and the response to the same bilaterally presented input. Importantly, the BD was no longer present when stimulation with large mismatches in place were delivered to children with full insertions of both devices [28]. Bilateral stimulation with smaller mismatches in place had little effect on the BD at comfortably loud current levels [28] although slightly greater effects were noted at lower levels in adult cohorts [30, 31]. Similar to the electrophysiological results, there appears to be some tolerance in behavioral data for slight mismatches in place of stimulation between implants; binaural sensitivity is still observed for cases in which mis-matches of up to ~2–3 mm occur ([32, 33]).

The electrophysiological BD study was also helpful in assessing binaural coding of ILDs in children. Significant changes in BD amplitude were found with increases in ILD, suggesting a change in bilateral brainstem activity [28]. Moreover, children increasingly lateralized these sounds to one side of their head as BD amplitude increased. In later work, Gordon and colleagues found that perception of ILDs was established at very early stages of bilateral implant use even for children who were older and heard through one implant for most of their lives [34]. This was consistent with findings that most children are able to discriminate stimuli containing ILD cues when tested after longer periods of bilateral implant use [26, 35]. More recently, ILD sensitivity in the envelope of short pulse trains was shown to be slightly reduced in children with long bilateral implant use (simultaneously and sequentially implanted) compared to normal hearing peers listening to clicks [34] (Figure 5A).

By contrast, studies using electrically pulsed signals reveal that children's sensitivity to ITDs is weak relative to their ILD sensitivity. Indeed, Gordon and colleagues initial impression was that ITD sensitivity was absent in most children with bilateral implants with similar findings from Litovsky and colleagues [26]. Weak detection of ITDs was recently reported by Gordon et al. to emerge in children with over 4 years of bilateral implant experience [34]. The sensitivity to these cues was significantly poorer than normal as shown in Figure 5B. Both responses to ILD and ITD were fit with logit regression curves and the mid-point (0.5) calculated for both cues. The linear relationships plotted for each of 3 groups of children indicated that when ITDs were presented with levels weighted to one side, ITD shifts to the opposite side were required to achieve balanced percepts. This time-intensity trading was very specific for children with normal hearing listening to acoustic clicks (27 μs shift in ITD for every 1 dB of ILD). Although the direction was similar for bilaterally implanted children listening to single electrical pulses, the shifts in ITD were relatively large (97–153 μs for every 1 CU shift in ILD). This means that ITD sensitivity is much weaker than normal in children with bilateral implants. These data reflect the typical exposure to binaural cues by children using bilateral CIs. Whilst they have access to ILDs through their bilateral devices, they continue to lack consistent exposure to ITDs in daily listening, thereby deteriorating their ability to detect these cues when provided under controlled experimental conditions through direct stimulation. Yet, the emergence of weak ITD detection with long bilateral implant experience suggests that children could be developing unique strategies of listening to bilateral electrical input under both direct experimental conditions as well as through their devices ([11]as discussed above). Insert Figure 6

An example of unique binaural listening of direct electrical stimulation comes from a study from Gordon and colleagues [36], in which bilaterally implanted children were reported to inconsistently hear a fused bilateral image in experimental conditions. As shown in Figure 6A, children frequently indicated that they heard 1 rather than 2 sounds when listening to simultaneous pulse trains from paired apical implant electrodes containing ILDs. As discussed above, these inputs were likely lateralized to one side as shown in similar cohorts of children [34, 35]. However, when bilateral input was presented with ITDs at balanced levels (ie. no ILDs), children with bilateral implants responded at chance levels when asked if they heard 1 or 2 sounds [36] (Figure 6B). This means that, without ILD cues, direct bilateral cochlear implant input is difficult for children to fuse into one image. The lack of ITD lateralization at early stages of bilateral device use under similar conditions could thus be explained in part by an inability to fuse bilateral input. If this poor binaural fusion continues despite long term bilateral implant experience, the later emergence of ITD detection reported above [34] might reflect an abnormal strategy used by these children to detect long ITDs. Such strategies may not be useful for shorter ITDs more typically needed for spatial listening. In the same study, reaction time and pupilometry were used to gauge listening effort involved during the binaural fusion task across groups [36]. Clear increases in both of these measures occurred with decreases in perception of a single fused binaural image. This suggests that mismatches in hearing between the two ears make listening more effortful for both children with normal hearing as well as for children with bilateral implants. It may therefore be important to correct for inaccurate binaural cues by improving programming of bilateral implants and better coordinating the speech processors as previously suggested [7, 24, 37].

A related finding with implications for binaural sensitivity comes from measures of binaural masking level differences (BMLDs), which is akin to SRM, in that the task involves segregation of target from noise through use of binaural cues. Van Deun and colleagues [38] presented children with encoded temporal information at one pair or multiple pairs of electrodes, and compared performance with either diotic (target and noise having the same binaural cues), or dichotic (target and noise presented with different ITD values) conditions. In the BMLD paradigm, binaural benefits of dichotic condition are thought to arise from a de-correlation of the signals between the two ear, which can produce dynamic ITDs and ILDs that are potentially available for extracting information about the target in the presence of the noise. More specifically, interaural de-correlation might be providing listeners with cues regarding the spectral structure of the target. In this study, children demonstrated BMLDs of a few dB, suggesting they were sensitive to interaural decorrelation of temporal envelope in dichotic listening conditions. As reported above, because many children with bilateral CIs are weakly sensitive to ITDs if at all, this finding indicated that the unmasking conditions revealed sensitivity to dynamic interaural level differences (ILDs), or interaural de-correlation of temporal envelope cues.

An interesting issue regarding studies with single pairs of electrodes is that it is difficult to interpret how they will compare to speech processing with multiple channels of stimulation. In another recent study [39], binaural unmasking was measured with multiple and single pairs of electrodes. Children with bilateral CIs performed similarly in the multi-electrode conditions and in the single-electrode conditions, and their performance pattern was similar to what was found with NH children who listened to simulations of CIs. Interestingly the results were not predicted from whether those children had good vs. poor ITD sensitivity, suggesting that the auditory cues used for binaural unmasking and binaural spatial hearing may not be the same. Overall, one of the main advantages gained from binaural unmasking is the improved ability of bilaterally implanted children to hear speech in noise at lower (worse) SNRs.

V. CONSIDERATIONS REGARDING AUDITORY PLASTICITY

As reviewed above, children with early onset deafness use their bilateral cochlear implants differently than adults. Although neither of these bilaterally implanted groups receives access to accurate binaural cues (as reviewed above), the increasingly abnormal findings in children suggests a unique vulnerability of the auditory system to the loss of normal hearing from both ears in early development. This finding might appear contrary to the notion of increased plasticity in children than adults. Yet, as will be discussed here, large developmental changes observed along the auditory pathways with implant use in children do not always occur in expected directions. The differences from normal reflect the atypical input provided by cochlear implants to children with hearing loss.

For many children, the loss of normal bilateral input begins during the period of deafness and continues while they use a unilateral cochlear implant. Development is driven preferentially from the unilaterally stimulated ear [40], compromising responses from the opposite pathways and potentially disrupting binaural hearing. Efforts to avoid these changes include simultaneous bilateral implantation [41–44], and the use of a hearing aid in the unimplanted ear (bimodal device use) [45–48].

Children's poor ability to fuse direct electrical stimulation from pairs of bilateral CI electrodes may be particularly revealing. Perception of these inputs as one sound deteriorated with increasing asymmetry of brainstem function as measured by differences in in brainstem response latencies [36]. These asymmetries arise from sequential stimulation of one ear before the other [28, 49–52]. Of importance, the eIII-eV latency (neural conduction time from cochlear nucleus to midbrain)[53] remained arrested in children with early onset deafness across a wide range of ages with little stimulation from either side prior to implantation [53–55]. Rapid decreases in the eIII-eV were then measured over the first 6 months of unilateral cochlear implant use [53, 54, 56, 57]. Thus, it appears that the persistent immaturity of the bilateral brainstem pathway allows plasticity to be retained during bilateral deafness. Unilateral stimulation drives the brainstem toward maturation, possibly closing a sensitive period of developmental plasticity and leaving brainstem pathways from the opposite ear relatively immature (as measured by delayed latencies from the second implanted side [28, 49–52]). Unilaterally stimulated brainstem neurons will also be deprived of bilateral input, which is primarily inhibitory from the ipsilateral side [27]. Fortunately, these connections are retained, as shown by clear binaural differences (BDs) in brainstem responses in both children [28] and adults [30] with bilateral CIs. This means that binaural processing in the brainstem may be altered by unilateral implant use but not obliterated. Asymmetric timing in the brainstem is in agreement with functional findings; although children's sensitivity to small ILDs [7, 34] emerges very quickly after bilateral implantation [34], detection of timing cues are relatively poor [7, 25, 34, 35], take many years to emerge [34], and appear to be weighted to the first implanted ear [34] as discussed above. Some of these listening challenges may contribute to or even result from poor binaural fusion of direct electrical stimulation [36] as also discussed above.

The degree of asymmetry in brainstem function is generally in line with a number of behavioral findings demonstrating that children listen better with their first than second implanted ears [58–60]. Yet, these associations could also reflect changes mediated in more central areas of the auditory system [61]. Cortical activity measured in dipole moment (nAm) by electroencephalography and located in left and right auditory hemispheres revealed reorganization with unilateral implant use as summarized in Figure 7 from 4 groups: 1) normal hearing children, 2) children using a right unilateral cochlear implant, and two groups of children receiving bilateral implants 3) simultaneously implanted or 4) sequentially implanted after use of a right sided cochlear implant. The sequentially implanted group was further divided by analyses of cortical activity by duration of unilateral implant use. Responses from localized sources in auditory cortices became significantly different from the simultaneous group by ~1.5 years, thus providing a cut point for the sequential group into "Long Delay" and "Short Delay" groups. Activity in both auditory cortices was strengthened from the right implant in the unilateral and Long Delay groups supporting the concept of an "aural preference" for the first hearing ear when bilateral implant is delayed for >1.5 years. In the normal hearing group, significantly contralateral responses for each ear were found and each cortex showed significant contralateral aural preference (7A). These findings were consistent with data in animal models [62], and likely reflect cortical immaturity in this cohort [63]. An increased response to the left cortex was measured in the group with unilateral right implants (7B). Simultaneous bilateral implantation protected the normal pattern of responses (7C) while children in the Long Delay showed both an increased left auditory cortex response as well as an abnormal aural preference for the ipsilateral (first hearing right ear) in the right auditory cortex (7D). Mean (SE) dipoles in each cortex stimulated by each ear for all groups are shown (7E).

It is difficult to distinguish cortical from brainstem contributions to behavioral findings. Reorganization of cortical activity may be promoted from a lack of contralateral inhibition to bilateral brainstem nuclei during the period of unilateral listening but it is also possible that the cortex reorganizes in response to altered binaural cues ascending through a brainstem which became preferentially driven from one side. Moreover, the role of descending projections from the cortex to midbrain and brainstem is unknown. Neuroanatomical reorganization of auditory cortex has also been found in children with asymmetric or unilateral deafness [64–68], confirming the influence of unilateral deprivation in development and further supporting the importance of early intervention [40, 69, 70].

Asymmetries in auditory activity and function persist with several years of bilateral implant use in children, suggesting more limited plasticity of the newly implanted ear than that of the first implanted ear. Whether development in the second implanted ear can ultimately "catch up" with the other remains unanswered. It may seem reasonable to define an age at which bilateral implantation should not proceed. However, while benefits from bilateral implantation in children can decline with age [13, 59, 71–77], there are many associated time-based issues to address. Consider for example, the suggestion by Graham and colleagues that adolescents should not be provided with a second cochlear implant [77]. The adolescent group may be amongst the poorest candidates based on abnormal cortical maturation, poor speech perception in the newly implanted ear compared to the first, inconsistent use of the second device, and inability to hear binaural timing cues [34, 77, 78]. Yet, several time-based factors might explain these findings including long durations of deafness experienced by the unimplanted ear which might decouple it from the secondary auditory cortices [79]. A lack of bilateral hearing/duration of unilateral hearing which is well beyond the optimal "Short Delay" of 1.5 years [40, 61]. A relatively mature stage of cortical development at which the auditory stimulation is being introduced [80–82]. Finally, the stage of teenage life at implantation which comes with unique social and educational pressures [83, 84] . Likely, all of these issues are important contributory factors which means that age alone cannot provide a meaningful explanation for the poorer outcomes of bilateral implantation demonstrated in some adolescent cohorts.

Access to hearing in early life is clearly important for development of the auditory cortex [79] and spoken language [85] and, as reviewed above, is also essential for binaural hearing. With that in mind, the type of bilateral input needed in early development is important to address. Gordon and colleagues have been exploring whether acoustic stimulation in an ear with some residual hearing can be integrated with a cochlear implant in the other ear to preserve the bilateral auditory system and promote binaural hearing [45–48]. Present studies are also investigating effects of implantation in children with unilateral deafness who in the past were not cochlear implant candidates and were thus unable to access binaural cues [86]. Again, time-based factors need to be considered as many of these children experience progressive deterioration of hearing [48]. This means that they experience different durations of deprivation either unilaterally or bilaterally depending on their history of hearing loss identification and treatment including time to implantation. All are coupled with advancing age and stage of auditory development. Early findings by Arndt and colleagues are consistent with the importance of bilateral input in childhood as shown by poorer outcomes in both adults and children with long durations of early onset unilateral deafness [87].

Efforts to preserve bilateral auditory function in both children and adults rest on the notion that auditory processing of bilateral input through bilateral implants or bimodal devices, while not normal, might provide benefits relative to adapting to unilateral hearing. Abnormalities in secondary cortical areas [66, 67, 78] for auditory processing coupled with findings of increased effort, poorer educational and speech language development [69, 88–90] in children with unilateral hearing, and benefits of both bilateral and bimodal use over unilateral implant use in children (as discussed above, Figure 1, and [91, 92]) suggest that this has been the right move. Nonetheless, future efforts to improve binaural integration and access to binaural timing cues will make better use of the bilateral pathways we are aiming to preserve by stimulating bilaterally during early development.

VI. SUMMARY

Spatial hearing skills are fundamental for the ability of children to function in complex auditory environments. The emergence of these skills during development is clearly hampered in children with bilateral CIs, and the reasons for these limitations are complex. The clinical approach is to attempt to maximize binaural sensitivity in order to improve spatial hearing, but the ability to present true binaural cues through processors is limited by today's technology. If that were possible, however, early exposure to appropriate cues would have the potential to help these children function more similarly to their NH peers. In addition, implantation varies with regard to whether children receive their CIs simultaneously or sequentially. The ability of the brain to reorganize is greatly affected by the early exposure that children have to appropriate cues, and it is clear that there are consequences of both unilateral and bilateral auditory deprivation during development.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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Spatial hearing skills are essential for children as they grow, learn and play.

Spatial hearing abilities rely on the ability of the auditory system to integrate inputs arriving at the two ears from sound sources that vary in location in space.

Binaural integration has exquisite mechanisms for capturing differences between the ears in time of arrival and intensity (ITDs and ILDs).

In children with normal hearing (NH), spatial hearing abilities are fairly well developed by age 4–5 years. Children who are deaf and hear through CIs show degraded abilities by comparison. The effects of auditory plasticity and deprivation on the emergence of binaural and spatial hearing show evidence for reorganized processing from both behavioral and electrophysiological studies.

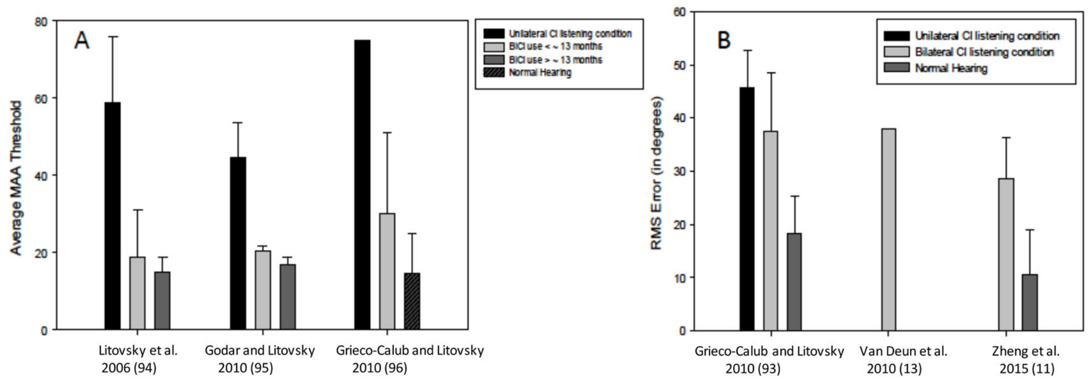

FIGURE 1.

A. Sound localization acuity as measured by MAA threshold for children using cochlear implants in bilateral and unilateral listening conditions as presented in three studies (NM = MAA was not measurable). Data come from Litovsky et al. (2006; 94), Godar et al. (2010; 95) and Grieco-Calub and Litovsky (2012; 96). B. Group mean RMS error in degrees presented in three studies comparing bilateral listening conditions to a unilateral listening condition and normal hearing control (* = No standard deviation reported for group mean RMS error). Data come from Grieco-Calub and Litovsky (2010; 93), Van Deun et al. (2010; 13) and Zheng et al. (2015; 11).

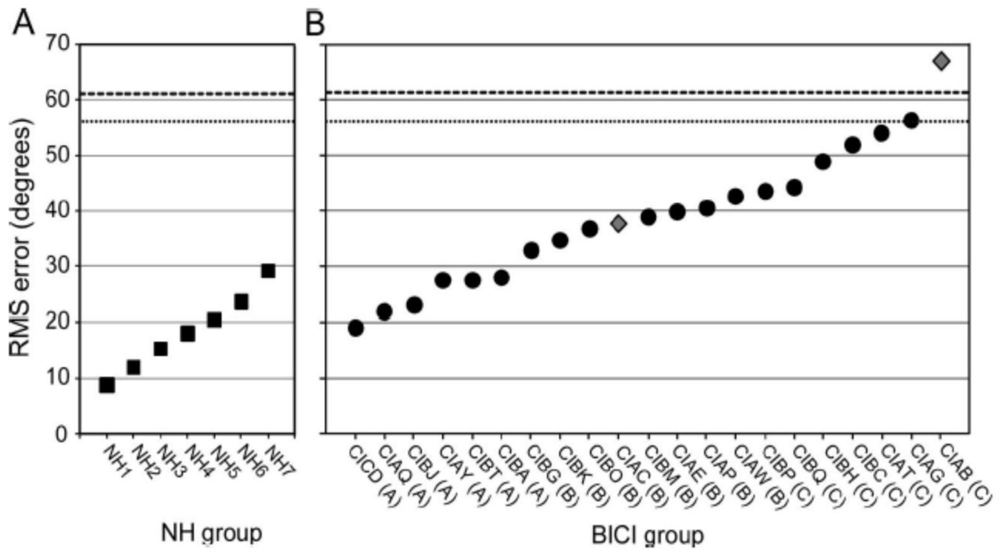

FIGURE 2.

Individual children's root mean square (RMS) error values are shown for children with normal hearing (NH) in panel A and children with bilateral CIs in panel B. NH children were 5 years old and CI users ranged in age from 5–14. For each group, data are sorted from lowest to highest errors along the x-axis. In both panels, data are arranged along the x-axis from the smallest to largest RMS errors (better to worse performance). In the bilateral group, the letters in the parentheses under each subject's data point indicate the subgroup that each child belonged to based on performance. In group A children had performance similar to that of NH children. In group B children were able to discriminate between the right and left but had poor ability to localize within each hemifield. Finally children in group C had poor ability to localize or discriminate between right and left. The dotted lines represent chance performance for either a 7-loudspeaker or a 15-loudspeaker setup, respectively (this is Figure 2 from Grieco-Calub and Litovsky, 2010 [93]).

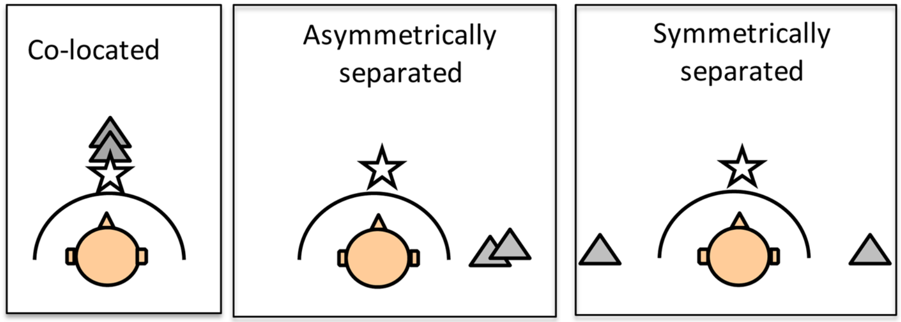

FIGURE 3.
Spatial configurations used in the studies on spatial release from masking. From left to right, panels show conditions with target speech in front, and interferers either in front, distributed asymmetrically around the head or distributed symmetrically around the head.

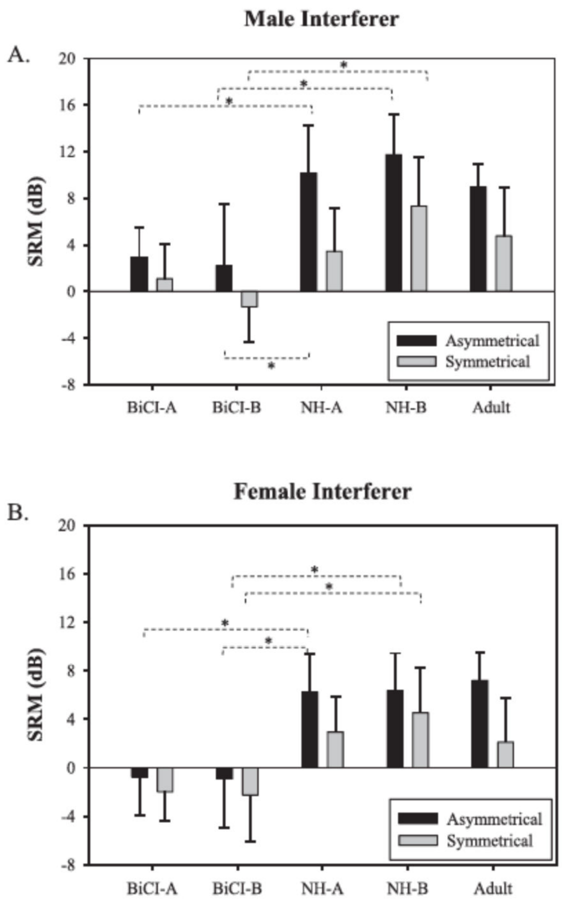

FIGURE 4.

SRM values are plotted for normal hearing (NH) adults, and for groups of children with different ages, with either NH or with bilateral CIs. A and B refer to younger or older, respectively. The chronological ages of the NH groups were on average 4 years 9 months (NH-A) and 5 years 2 months (NH-B). Ages were 7 years 5 months and 8 years 3 months for the BiCI-A and BiCI-B groups, respectively. These data are from Misurelli and Litovsky (2015)(12).

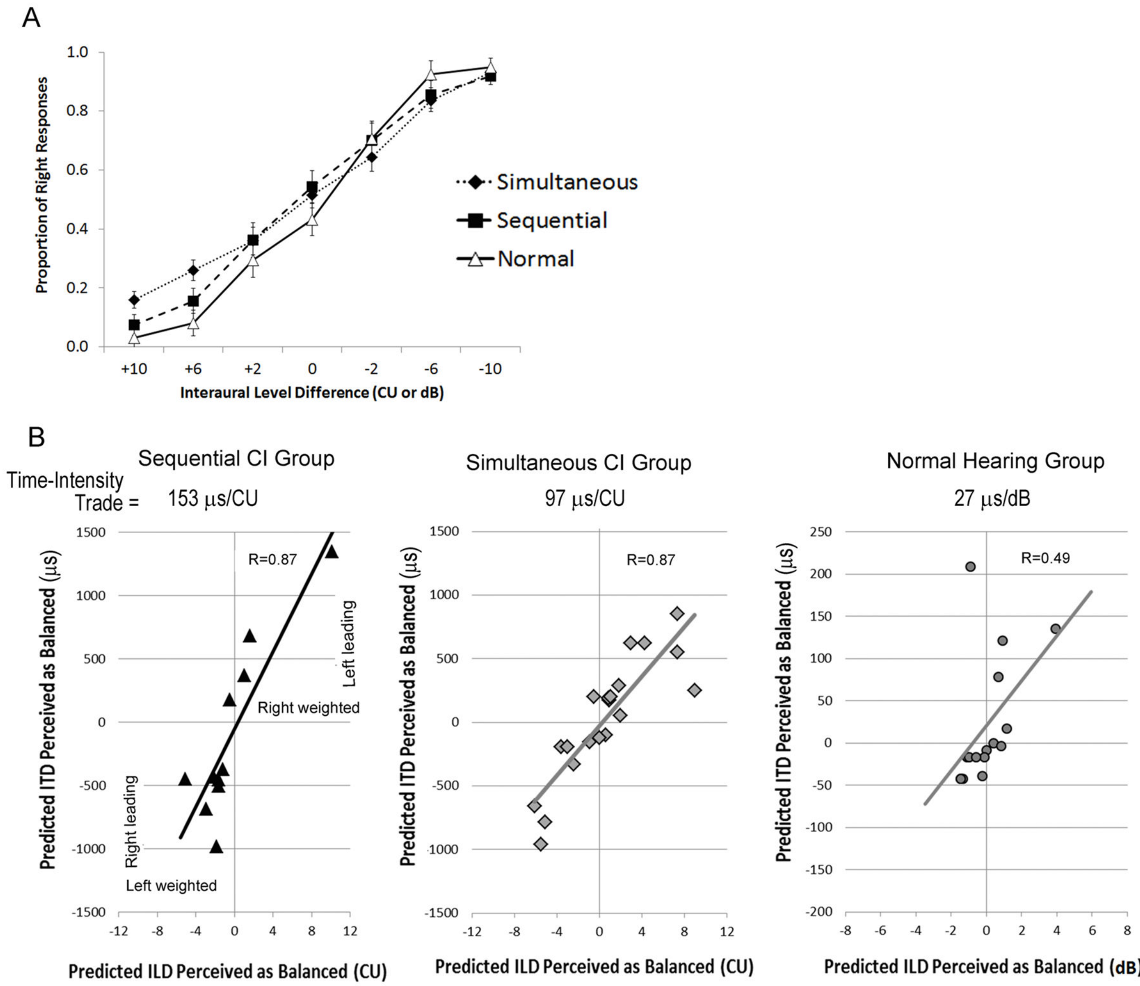

FIGURE 5.

A. Experienced bilateral CI users and normal hearing peers perceived changes in ILDs as these cues moved from left to right weighted. Interaural level differences (ILDs) in CI users represent differences in CU and dB re: 20 Pa in the normal hearing group (,0.08 dB re: 100 mA per acoustic dB change in ILD.) (Mean data ± 1SE from Figure 3 from Gordon et al., 2014). B. Time-intensity trading revealed by plotting predicted balance (ie. 0.5 responses calculated from logit regressions of responses) to ILD and ITD cues. Positive values are right weighted ILDs and left leading ITDs. ILDs weighted to one side shifted balanced perception toward opposite leading ITDs in all groups. Time-intensity trading shifts were much larger for the two groups of bilaterally implanted children than the normal hearing peer group (Figure 6 from Gordon et al., 2014)[34].

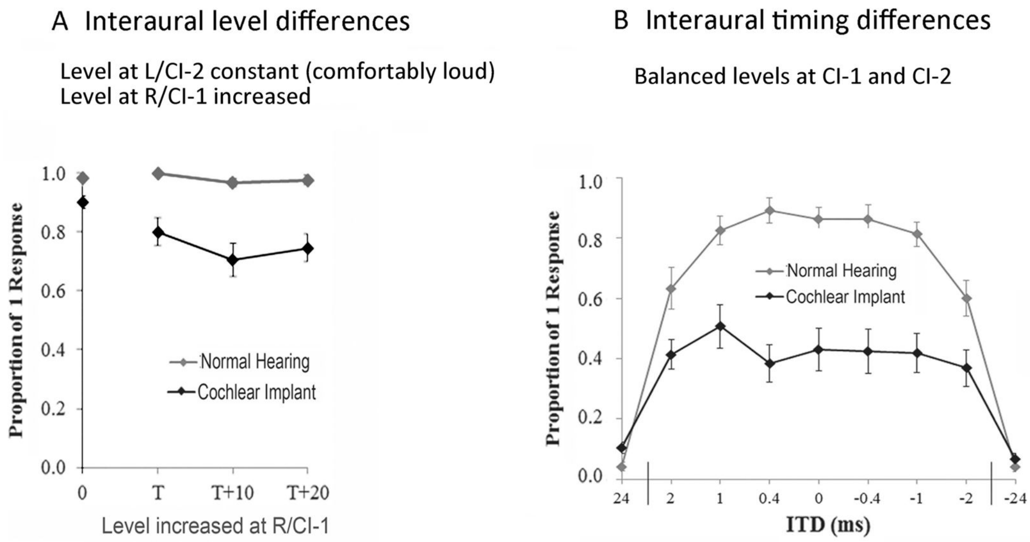

FIGURE 6.

A: Children with bilateral implants (n=25) consistently perceived one image when presented with unilateral (Level in CI-1=0, CI-2 at comfortable loud level) and 21 bilateral input (increasing CI-1 level, CI-2 at comfortably loud level) albeit less frequently than did NH peers (n=24) ($p < 0.0001$). 6B) Children with bilateral implants respond at chance to bilateral balanced stimuli with balanced input and significantly less often than the normal group ($p<0.0001$). When ITDs are extremely large (24 μs), both groups indicate a lack of binaural fusion, demonstrating understanding of the task. (Mean data ± 1SE from Figure 5, Steel et al., 2015)[36].

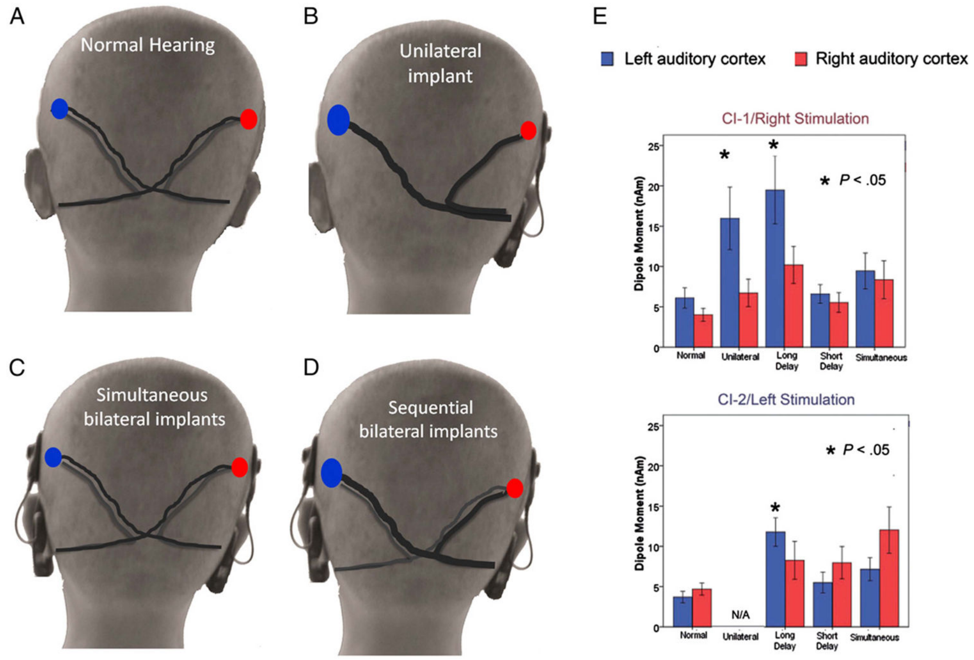

FIGURE 7.

A–D, Schematic representations of the strength of pathways from each ear (right ear in red, left ear in blue) to the contralateral and ipsilateral auditory cortices are shown. E, Mean (SE) dipoles measured in the left (blue) and right (red) auditory cortices (Gordon et al., 2013) Responses to pure tones in each ear are stronger in the contralateral than ipsilateral cortex in children with normal hearing. Bilateral pathways are essentially symmetric in children receiving bilateral input in early development (normal-hearing, simultaneous bilateral implants, short delay between implants). Unilateral right implant use strengthens pathways to both contralateral and ipsilateral auditory cortices, increasing dipoles in the left auditory cortex and reversing aural preference to the first implanted right ear. CI-1, first implant; CI-2, second implant. (Figure 4 from Gordon et al., Pediatrics, 2015)[40].

Table. 1A

Demographic information for studies shown in Figure 1A.

	Litovsky et al., 2006	Godar et al., 2010	Greico-Calub et al., 2012
Speaker locations	±70°, ±60°, ±50°, ±40°, ±30°, ±20°, ±10°, 0°	±90, ±80, ±70°, ±60°, ±50°, ±40°, ±30°, ±20°, ±10°, 0°	±70°, ±60°, ±50°, ±40°, ±30°, ±20°, ±10°, 0°
Sample size	13 BiCI 6 UniCI	10 BiCI	27 BiCI 12 UniCI
Age (years)	3 to 16 yrs	5 to 10 yrs	2.2 to 3 yrs
BiCI Experience (months)	2 to 14 mos	Interval I: ~3 mos Interval II: ~12 mos	5.5 to 19.5 mos
Sequential / Simultaneous	All sequential	All sequential	16 sequential, 3 simultaneous
Manufacturer	All Cochlear Corp.	9 Cochlear Corp., 1 Advanced Bionics	All Cochlear Corp.

Table. 1B

Demographic information for studies shown in figure 1B.

	Greico - Calub et al., 2010	Van Duen et al., 2010	Zheng et al., 2015
Speaker locations	±70°, ±60°, ±50°, ±40°, ±30°, ±20°, ±10°, 0°	±60°, ±45°, ±30°, ±15°, 0°	±70°, ±60°, ±50°, ±40°, ±30°, ±20°, ±10°, 0°
Sample size	21 BiCI	30 BiCI	19 BiCI
Age (years)	5 to 15 yrs	4 to 15 yrs	4 – 9 yrs
BiCI Experience (months)	3 to 28 mos	12 to 44 mos	13–51 mos
Sequential / Simultaneous	All sequential	All sequential	16 sequential, 3 simultaneous
Manufacturer	17 Cochlear Corp., 3 Advanced Bionics, 1 Med-EL	All Cochlear Corp.	All Cochlear Corp.