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Review

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. These skills provide critical cues for determining the locations of sources in the environment, and enable segregation of important sounds, 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, most 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, these children 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.

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1. 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 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 judgments (Macpherson and Middlebrooks, 2002).

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 (Middlebrooks and Green, 1991; Blauert, 1997; Yin, 2002).

In children with normal hearing (NH), spatial hearing abilities are fairly well developed by age 4–5 years (Litovsky, 2011; Litovsky, 2015). 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 Litovsky et al. (2012), Kan and Litovsky (2015)). 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.

2. 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) (Litovsky, 1997; Hartmann and Raked, 1989). For recent reviews on this topic see also (Litovsky, 2011, 2015). 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 (Zheng et al., 2015). Fig. 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 Fig. 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 low as typically developing NH children. Fig. 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,