Binaural and Spatial Hearing in Implanted Children

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Ruth Y. Litovsky

Introduction

Children with normal hearing (NH) utilize information that arrives at the two ears in order to perform a multitude of tasks in their everyday listening environments. In the field of audiology, the question regarding provision of auditory input to one vs. two ears has been around for many years. Several decades ago, questions revolved around bilateral amplification with hearing aids, and researchers generally thought that children should be fitted with amplification in both ears in order to maximize the stimulation of the right and left auditory pathways. Additional benefits that were of interest, but only measured in patients with usable hearing in both ears, were related to binaural benefits. The potential benefits from having two usable ears will be discussed in detail below as they relate to the binaural cues that are available to listeners when using acoustic hearing, or electric hearing through cochlear implants (CIs).

In the past decade there has been a steep increase in the number of children who are deaf and implanted bilaterally. At the start of the millennium, this clinical approach was somewhat novel and considered to be lacking in evidence regarding benefits. However, the clinical trend has shown momentum towards bilateral stimulation, with justification revolving around several main issues. First, if hearing is usable in both ears, and if the inputs arriving at the two ears are coordinated in the time domain, then the auditory system uses binaural hearing. That is, the brain receives crucial information regarding the location of sound sources, enabling listeners to localize sounds of interest. In this ideal scenario, the brain also compares inputs from the two ears in order to segregate speech from background noise. Second, under less ideal conditions, with inputs to the two ears arriving in an uncoordinated fashion, the auditory system receives bilateral hearing. There are crucial auditory cues that allow a listener to gain access to the target speech signal and to localize sounds in a fairly crude manner. Nonetheless, the access to this information can lead to improved hearing in everyday listening situations. Third, regardless of whether binaural or bilateral hearing is utilized, there are dual-implant assurances; the fact that both ears are stimulated has important benefits including assurance that the better ear was implanted, which is crucial for language acquisition, and also assurance that if one of the CI devices fails to operate the child will not be "out of sound." This chapter will first review binaural hearing and acoustics that can provide binaural and/or bilateral inputs. Second, this chapter will describe the methods that are used to evaluate bilateral and/or binaural benefits in children. Third, this chapter will review the measured outcomes as indicated through behavioral testing.

R.Y. Litovsky, Ph.D. (✉)
Waisman Center, University of Wisconsin—Madison, 1500 Highland Ave, room 521, Madison, WI 53705, USA
e-mail: Litovsky@waisman.wisc.edu

Binaural Cues

Throughout development, in most social and learning environments infants and children are faced with auditory signals that arrive from multiple locations; it is important to understand how acoustic inputs give rise to spatial cues when sound sources reach the ears. Sounds that occur in the horizontal plane and reach the ears from the side will naturally create differences in time of arrival between the ears, because sounds reach the near ear before the far ear. In addition, the near ear will have a greater intensity than the far ear. For example, as shown in Fig. 10.1a, for a sound arriving from 90° to the left, an adult head will have ~0.7 ms interaural timing difference (ITD) favoring the left ear. In particular, ITDs play a role at low frequencies (<1500 Hz). At high frequencies an acoustic "shadow" is created which results in interaural intensity (or level) differences (IIDs or ILDs)

N.M. Young, K. Iler Kirk (eds.), *Pediatric Cochlear Implantation*, DOI 10.1007/978-1-4939-2788-3_10

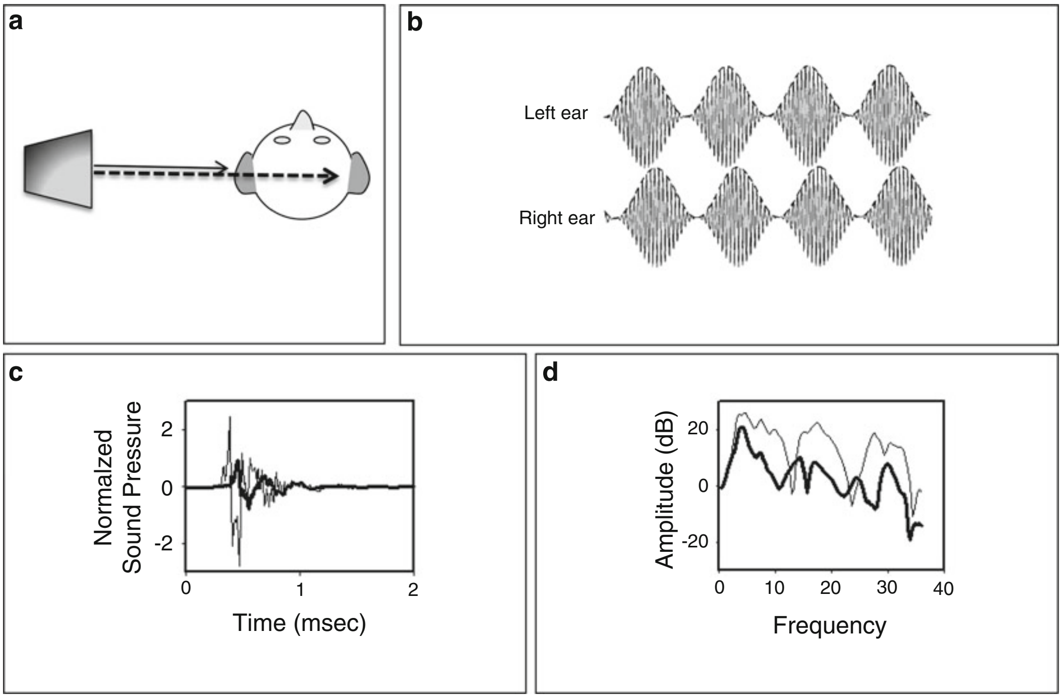

Fig. 10.1 Localization cues are depicted for a sound arriving from 90° to the left. (**a**) The head of an adult is shown with sounds arriving at the two ears, with a ~0.7 ms interaural timing difference (ITD) favoring the left ear. (**b**) An example of a high frequency stimulus with an amplitude modulation is shown, whereby ITD cues are also available from differences in the timing of the envelopes of the stimuli. (**c**) Stimuli reaching the two ears are shown on the same graph, to depict the interaural time difference between the *thinner* and *thicker lines* (left and right ears, respectively). The same stimuli, reaching the two ears, are shown to depict the difference in amplitude across the two ears

between the ears. IIDs or ILDs are frequency dependent but can be as large as 20 dB. For amplitude modulated sounds (e.g., speech) ITD cues are also available from differences in the timing of the envelopes (slowly varying amplitude) of the stimuli, as shown in Fig. 10.1b. Stimuli that reach the auditory system after entry through the ear canals, and that are coordinated across the ears in the time domain, will provide listeners with binaural cues. Examples of these cues are depicted in panels C and D, where differences between the ears are shown in the time domain (C) and in the spectral domain (D). It should also be noted that a different set of cues helps in the localization process for sounds that occur in the vertical plane. Those cues arise from directionally dependent filtering of sounds by the head and pinna. Thus, when sounds vary location in elevation, their spectral content is "shaped" differently for sources arriving from above, in front or below. CI processors inherently have degraded spectral resolution, and high frequencies are cut off above ~8000 Hz, rendering the availability of vertical-plane cues minimal or absent. Thus, the current chapter focuses on perceptual effects that have been studied in the horizontal plane. More detailed reviews of localization cues can be found in Blauert (1987), Middlebrooks and Green (1991).

One important note regarding development in early childhood pertains to the fact that head size changes as children grow, particularly during the first few years of life. In fact, a source arriving from 90° to the side will generate a substantially different set of binaural cues for a young infant than for an older child or an adult. Thus, as the head size changes throughout development, the correspondence between location and directional cues has to undergo constant recalibration (Clifton et al. 1988).

Methods Used to Evaluate Binaural and/or Bilateral Inputs

The patient population being evaluated determines which methods are appropriate for perceptual testing. When evaluating binaural hearing we are often interested in the general category of spatial hearing abilities, which include three primary areas: (1) sensitivity to binaural cues, (2) sound localization, and (3) speech understanding in noise. For all three areas, the easiest population to test is adults with NH, because listening is intuitive to them, and instructions about what aspects of the sound they should pay attention to and report on are fairly straightforward. Older children with NH, for similar reasons to those stated for adults, are also generally easy to involve in testing. However, the population of interest here is children who are deaf and fitting with CIs.

Devising tests is rather challenging for this population because listening is not always intuitive, and perception in the spatial domain is an emerging ability that is likely to depend on experience in a more protracted time scale than the emergence of spatial hearing in NH children. Some of the anecdotes collected in the Binaural Hearing and Speech Lab at the Waisman Center (discussed by Litovsky 2013) are informative regarding the issues that most fundamentally affect children who are fitted with bilateral CIs; these children often report that they do not perceive sounds as arriving from particular locations. They appear to develop these skills with experience, in particular by matching what they hear to what they see. Although little is known about the mechanism through which auditory-visual inputs are integrated in these children, the studies discussed below highlight the use of behavioral testing utilizing visual markers that enable the children to indicate where the sound sources are perceived to be.

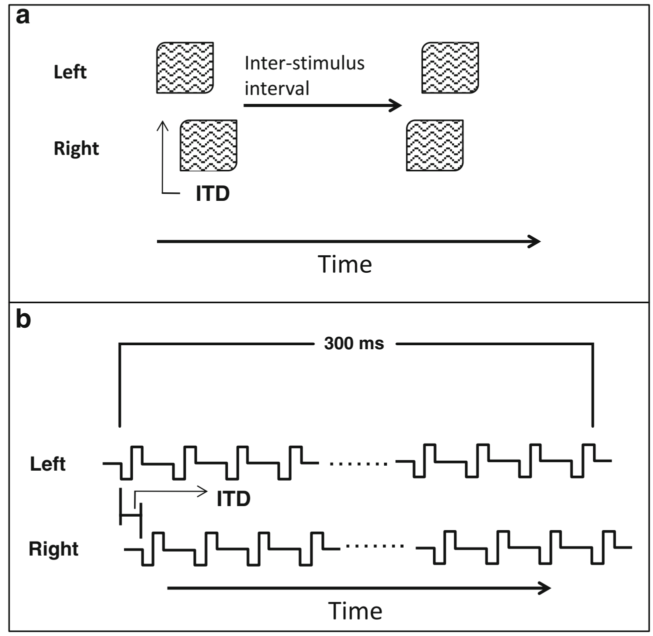

Fig. 10.2 (**a**) For stimuli presented over headphones schematics of the temporal sequence of binaural stimuli is shown. First, a pair of stimuli arrives at the left and right ear with an ITD favoring the left. Then, followed by a brief delay a second pair of stimuli arrive and the right and left ear with an ITD favoring the right. (**b**) Schematic of pulsatile stimuli presented to the cochlear implant arrays with binaural stimulation. In this example biphasic pulses are presented to the left ear followed by the right ear with a fixed ITD

Methods to Measure Sensitivity to Binaural Cues

Much of the literature that is related to binaural and bilateral hearing focuses on questions related to the acuity of the auditory system: the extent to which listeners are sensitive to small differences between sound source locations, or between ITD/ILD values that are presented to listeners over headphones. On any given trial, the values of ITD or ILD are presented over several intervals, and the listeners' task is to determine whether the sound was perceived towards the right ear or left ear. ITD or ILD values are typically varied using a staircase procedure, whereby the values are decreased following a correct response and increased following an incorrect response. The goal in the experiments is to provide the child with enough information to compare on two stimulus intervals; one example is a stimulus that is presented from the right followed by the left, or the left followed by the right. On any given trial, the child is asked to report whether a sound source was perceived to move right-left or left-right. Feedback regarding correct responses helps the child learn what cues to focus on and achieve best performance. A schematic of the temporal sequence of stimuli is shown in Fig. 10.2. Panel A shows stimuli presented over headphones to NH listeners; these stimuli can vary in content but typically consist of brief tone bursts or noise bursts. The first set of bursts shows a stimulus that reaches the left ear before the right ear; hence if the child is able to extract binaural cues from the stimulus, s/he will perceive a sound on towards the left ear. The second set of bursts have the opposite temporal sequence, with the right ear leading the left ear, thus the child would perceive a stimulus near the right ear. In an experiment, this trial type and one in which the opposite sequence occurs are presented in random order. Furthermore, the size of the ITD is varied, in order to find the smallest ITD for which the child can reliably hear the difference between left-right and right-left. In order to produce similar effects with ILDs (not shown), the levels of the stimuli in the two ears are adjusted to create perceptual images that are near the right or left ear, and a similar sequence of stimuli is presented.

Figure 10.1b shows examples of electrically pulsed signals that are used to make similar measurements, with deaf individuals who are fitted with bilateral CIs. This schematic (Litovsky et al. 2010) shows biphasic pulses, presented to select pairs of electrodes in the right and left ears, after extensive testing shows that the patient perceives the stimuli to produce similar pitch percepts, and that when the electrodes in the two ears are activated simultaneously, a fused auditory image is perceived (rather than independent sounds at the two ears). In order to establish precise levels of acuity, subject attention and motivation has to be very high, and thus little is known about binaural sensitivity in young listeners, particularly children with hearing loss.

A somewhat easier behavioral method that can be used to measure spatial hearing acuity in very young infants and children is typically done in the free field, using loudspeakers, but the same ideas as described above for ITD/ILD apply. Figure 10.3 shows a schematic diagram of loudspeakers placed in a room at 10° increments; the locations of the loudspeakers can be set so they are flexible, in order to allow presentation of sounds at smaller intervals, for children who show sensitivity better than 10°. The aim of this behavioral test is to find the smallest change in the location of a sound that the infant or child can reliably discriminate. In the schematic diagram, the illustration is for sounds that are emitted from 0° (front), followed by presentation to the right or left. The size of angle is determined by the child's performance. Typically, larger angles are used first, and once it is established that a child can discriminate changes from the front to the right vs. left at larger angles, smaller angles are used. Testing is most efficient if conducted using an adaptive staircase procedure (see Litovsky 1997; Grieco-Calub and Litovsky 2012), and finding the angle at which performance is above chance (>70.9 %; Levitt 1971). Estimates of spatial hearing can also be obtained by fixing the loudspeaker locations for sets of 20 trials at a time, and obtaining data at numerous angles, then fitting the data to a psychometric function and finding the angle at which performance reached >70.9 % correct (Litovsky et al. 2006a). There are pros and cons to each of these methods, particularly for children with CIs for whom location information can be difficult to extract and who may need to first learn the task with the fixed-angle method before proceeding to the adaptive angle method. It is noteworthy that the adaptive staircase procedure has been used with NH infants as young as 6 months of age (e.g., Ashmead et al. 1991), and both methods have been used with toddlers who are either NH or who use CIs, age 2.5 years (Grieco-Calub and Litovsky 2012). The ultimate goal in this task is to assess auditory location acuity, known as the minimum audible angle (MAA), which is defined as the smallest change in a sound source location that the listener can discriminate accurately and reliably (e.g., Mills 1958; Litovsky and Macmillan 1994; Litovsky 1997). A more complex task, described below, is one in which children are tested on their spatial mapping ability, that is, on how well they know where a sound is coming from, rather than only discriminating its location based on hemifields. A significant issue to note here is that a child's ability to discriminate right vs. left might not automatically provide the necessary cues for a map of space and for accurate knowledge about where sounds are coming from (Hartmann and Rakerd 1989; Grieco-Calub and Litovsky 2010).

Methods Used to Measure Sound Location Discrimination and Sound Localization

In everyday environments, the listener is typically interested in finding a source of importance (such as the voice of a parent or teacher, a musical instrument or a toy), and the subsequent task is to be able to direct attention to the source, extract meaning from its content and respond to the content. These abilities are essential for achieving successful communication. To aid in this process, the ability to quickly identify the location of a source can be quite useful. In order to achieve this task, the listener needs to have a well-developed map of auditory space that organizes locations of sounds in the world relative the listener's head and relative to other sources in space. To date, research has produced a plethora of information about this ability in NH listeners, who have been tested through methods that incorporate verbal reports of locations (e.g., Wightman and Kistler 1989), eye gaze (Populin 2008), pointing towards the source location with the finger or head (see Middlebrooks and Green 1991), or pointing to a location on a proxy for space such as a spherical model of auditory space (Good and Gilkey 1996). The cognitive load required for these tasks might be high and training can take numerous hours before the data are repeatable. Thus, simplified versions of these tasks have been implemented in children. Nonetheless, the error rates observed in these experiments suggest that adults can generally localize sounds with a resolution ranging from a few degrees to ~10°.

When developing tests for young children, we have focused on utilizing ecologically valid methods that attract the children's attention, provide motivation, and provide results that are replicable. With children ages 4–5 years and older, interactive computerized testing platforms have been successful in that the children find the task intuitive and the response method is learned relatively quickly. The child typically sits in a room facing an array of loudspeakers, similar to the distribution shown in Fig. 10.3. A computer monitor placed under the loudspeaker in the front position displays the array, with icons corresponding to each location. On each trial a sound is emitted from one of the loudspeakers and the child uses a computer mouse to indicate on the computer monitor which loudspeaker emits the sound (Grieco-Calub and Litovsky 2010; Litovsky and Godar 2010).

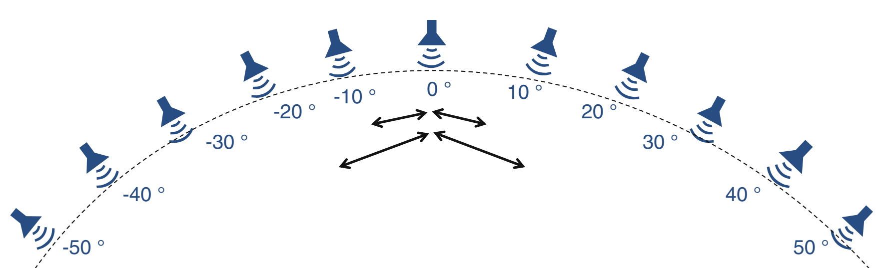

Fig. 10.3 Schematic diagram of loudspeakers placed in a room at 10° increments

Testing toddlers is, as indicated above, more challenging than testing older children, because instructions are more difficult to give, attention spans are much shorter, and redirection of attention away from distractions and to the task at hand can be more challenging. Towards that end, a novel method for assessing spatial hearing skills in toddlers was recently developed (Litovsky et al. 2013), whereby the child reaches for a sounding object that is hidden behind a curtain. The child faces an array of loudspeakers that are hidden behind an acoustically transparent curtain, and is shown a toy that will be the object of interest and attention. The toy is hidden behind the curtain at a location corresponding to one of the loudspeakers, and at the onset of the trial, the child hears a prerecorded voice from one of the locations, inviting them to find the object; by reaching through the correct space in the curtain the child can obtain the toy and is reinforced for a "correct" response. This Reaching For Sound (RFS) methodology lends itself to testing over dozens of trials with great interest on the part of most young children, and the method is successful with toddlers as young as 18 months of age. The RFS method is robust beyond sound localization measures and has been implemented in recent studies on speech perception and discrimination of toddlers with CIs (Hess CL. Speech discrimination and spatial hearing in toddlers with bilateral cochlear implants. Unpublished PhD Dissertation and University of Wisconsin-Madison 2013).

Methods Used to Measure Speech Understanding in Noise and Related Phenomena

The ability of a child to segregate speech from noise in complex auditory environments has been studied primarily in NH children, with a growing interest lately in understanding also how this ability emerges in children who are deaf and use CIs. There are some clear similarities between the two populations, under conditions that maximize spatial cues that both populations of children are able to hear. The goal of controlled experiments on speech intelligibility in noise is to measure the ability of children to identify the content of speech sounds that they know; rather than testing vocabulary, these tests only utilize stimuli that the children have been familiarized with, and are known to the children. A second goal is to create scenarios that mimic everyday listening situations, such as when a voice of interest is facing the child in front (target speech), and other voices (maskers) occur from locations that are either co-located with the target speech or spatially separated from the target speech.

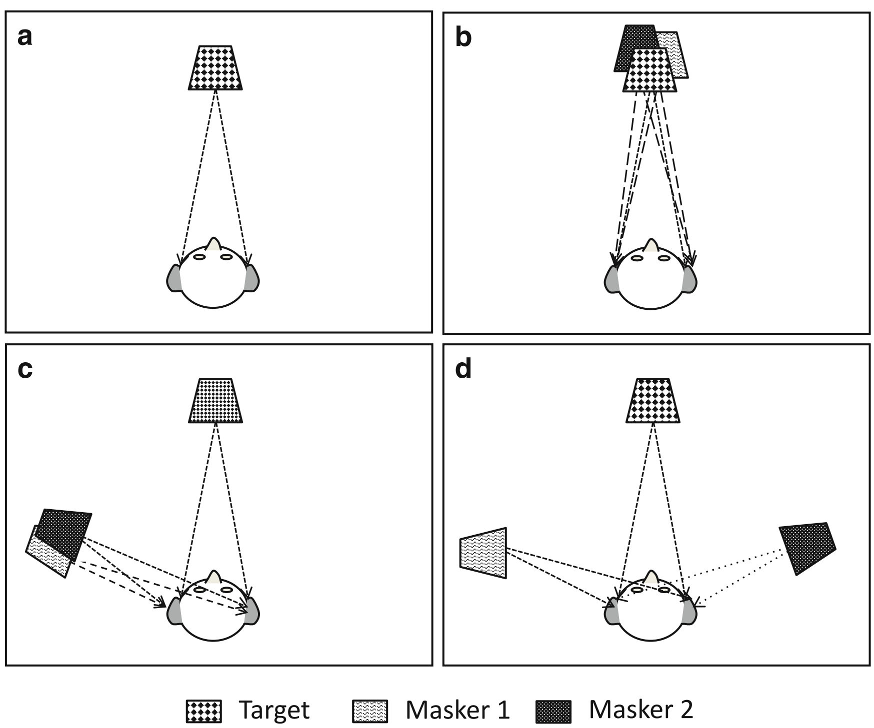

Fig. 10.4 (**a**) Target speech is presented from the front, in quiet. (**b**) Target speech is presented from the front and two maskers are presented from the front as well. (**c**) Here, there are two maskers and both are displaced towards the left ear. There are six signals in total, three at each ear from each source. However, the directional cues provided by the target are different from those of the maskers. In addition, as will be described below, the fact that the target speech reaches the right ear with a favorable signal-to-noise ratio (SNR) means that the "head shadow" effect creates a favorable listening condition. (**d**) In this symmetrial configuration the target speech is in front, and the two maskers are presented from the right and left, creating a situation in which there is no 'better ear' and the listener must use binaural cues to spatially segregate the speech from maskers

Figure 10.4 shows the four scenarios that are most informative about the ability of children to use spatial cues to segregate speech from background interferers, or maskers. Panel A shows the simplest case, in which the target speech is presented from the front, in quiet, and the stimulus reaches each ear. Panel B depicts an example of a masking condition with two maskers added to the front location. Each source emits sounds that reach both ears, creating a complex array of signals that need to be pulled apart in order for the child to extract meaning from the target speech. The benefit for speech intelligibility typically occurs when spatial cues are made available, in particular those shown in Fig. 10.4c; here, there are two maskers and both are displaced towards the left ear. There are six signals in total, three at each ear from each source. However, the directional cues provided by the target are different from those of the maskers. In addition, as will be described below, the fact that the target speech reaches the right ear with a favorable signal-to-noise ratio (SNR) means that the "head shadow" effect creates a favorable listening condition.

For many children, the condition shown in Fig. 10.4c results in an effect known as spatial release from masking (SRM), whereby performance is better compared with the condition in which maskers are co-located with the target (Litovsky 2005; Misurelli and Litovsky 2012). Performance is typically measured by obtaining the speech reception thresholds (SRTs) in quiet, as well as the co-located condition and the spatially separated conditions. SRM is thus quantified as the difference in SRTs between the co-located and separated conditions. In SRT terms, higher values indicate poorer performance, i.e., that a larger SNR was required in order for the child to correctly identify the target words. Thus, if SRTs are higher in the co-located than separated conditions, SRM would be positive, indicating that the child experiences a benefit when target/maskers are spatially separated. In other words, the child is able to take advantage of location cues in order to extract the meaning of the target words in the presence of the maskers.

Outcomes in Children Fitted with Bilateral Cochlear Implants

The following section described results from studies on binaural and spatial hearing that are relevant to pediatric bilateral CI users. As the data are considered, some of the limitations that occur in CI users will be discussed. These are summarized in Table 10.1.

Sensitivity to Binaural Cues

In the field of implantable auditory prostheses, the "gold standard" for testing exquisite levels of sensitivity to stimulation involves the use of direct electrical stimulation. This is unlike the free field, where the microphone picks up the signal and transmits it to the speech processor, which then acts on the signal in numerous additional ways. Instead, the microphone and speech processor are bypassed. Electrical stimulation is presented to the patient through research processors which allow the experimenter to stimulate electrodes along the cochlear array in a selective manner, and to tightly control the stimuli in each ear, at each electrode. In the case of binaural hearing this is particularly important, because the CI processors in the two ears are not temporally coordinated, which creates problems with the level to which ITDs are preserved with fidelity. In addition, the CI speech processor stimulates all electrodes at fixed-rate stimulation that is typically higher than the frequencies at which ITDs are easily encoded. In order to study binaural sensitivity one must therefore simplify the stimuli and maximize the possibility that patients will be able to extract information from the electrical pulses.

Figure 10.2b shows the type of stimuli that can be used, with simple trains of biphasic pulses, presented to select pairs of electrodes in the two ears. An ITD or ILD can then be imposed on these train pulses, to study the extent to which patients are sensitive to these cues. One key factor to keep in

Table 10.1 Limitations that occur in pediatric bilateral CI users

Site of limitation	Problem or limitation
Cochlear implant speech processor	Signal processing compromises acoustic cues: • Lack of temporal fine structure • Fixed-rate stimulation may not be ideal for capturing spatial hearing cues
Microphone	Compression distorts ILD cues
Cochlea	Spread of excitation along the basilar membrane leads to interaction amongst nearby electrodes
	Limited number of channels
	Poor specificity of stimulation on a frequency basis
Between the cochleae in the two ears	Potential mis-match in insertion depth, leading to mis-matched frequency inputs for electrodes that are anatomically matched in the two ears
Cochlea, auditory nerve	Neural degeneration; asymmetrical across the ears?
Binaural pathways	Degeneration of binaural circuitry due to lack of binaural inputs during development

mind is that binaural hearing in the acoustic system depends on the intrinsic wiring of inputs from the two ears whereby frequency-matched inputs are received at the level of the brainstem where ITD and ILD information is further processed. The studies on this topic in adults, in the past two decades, have shown that it is important to be able to stimulate electrodes that are matched by perceived pitch, because that indicates areas of the cochlea that stimulate auditory nerve fibers with the same frequency sensitivity (van Hoesel 2004; Litovsky et al. 2010). In fact, deliberate mis-matching of stimulation leads to the perception of binaural inputs diffuse or unfused, and those stimuli are poorly lateralized compared with pitch-matched inputs (Kan et al. 2013).

This background is critical towards our understanding of the issues that should be considered with young children who are bilaterally implanted, because at the clinical level the frequency allocation of information sent to the two ears is not deliberately matched by place of stimulation. Although there may be some matching across the ears by electrode number, if the two electrode arrays are not inserted with the identical insertion depth, a mis-match in frequency allocation across the ears is likely to occur. The extent to which children adapt to the potentially mis-matched inputs is not known. Further, little is understood regarding the extent to which children, whose neural pathways are stimulated at a time when neural plasticity is in place, are better than adults at compensating for this problem. Initial investigations on this topic suggest that children with bilateral CIs are able to use ILD cues to perceive sounds as occurring from the right or left; however, their ability to use ITD cues is poor. In contrast, when NH children are presented with a similar task using acoustic stimuli, they can reliably use either ITDs or ILDs to perform the same task (Salloum et al. 2010). This is not thought to be a developmental issue because ITD sensitivity on a right-left discrimination task is fairly well developed in NH children by age 4 (Van Deun et al. 2009): thresholds are reported to be, on average, 40 µs for 4-year-olds, 20–35 µs for 5–9-year-olds, and 12.5 µs for adults. The concern is that bilateral CI users are not receiving binaural inputs with fidelity during their everyday listening through their speech processors. Thus, when presented with these cues on a controlled experimental task, their auditory system may not be able to process the information in a useful manner. In contrast, ILD cues are received by the CI processors with greater fidelity, and all bilateral CI users seem to have sensitivity to those cues (for recent review, see Kan and Litovsky 2014). More recent and extensive studies in both NH children and in pediatric bilateral CI users are under way in the Litovsky lab at the University of Wisconsin-Madison. Results suggest that, similar to the Salloum et al. study, ILD sensitivity is easier to induce than ITD sensitivity. Moreover, children with onset of deafness after age 3 (postlingual) seem to have some access to ITD cues and perform better than children with congenital deafness (Ehlers et al. 2013; Litovsky 2011a, b; Kan and Litovsky 2014). The former are most likely able to rely on the fact that their auditory system was able to code that information prior to onset of deafness, and the cues that are provided during the experiments are stimulating pathways in the binaural system that had established ITD coding during development. This topic is of great interest in terms of future treatment of bilateral CI users, most of whom are congenitally deaf, and consideration should be given to advantages that might be gained through the development of CI processors that capture and present ITD cues.

Sound Location Discrimination and Sound Localization

In order to understand spatial hearing in children who are fitted with CIs, it is important to consider how the natural progression of spatial hearing emerges in NH infants and children. Thus, the standard to which CI users are compared can be considered in the context of expectations and rehabilitation. In NH infants, head orientation towards sound sources begins at birth as a reflexive response to an environmental stimulus. Newborns respond to sounds presented from the right vs. left in a reliable manner, although this head-orienting behavior is not conditioned and will only be observed for a limited number of trials (Muir et al. 1989). The head-orienting behavior is refined during the first 6 months of life and becomes an easily conditioned behavior through visual reinforcement (Moore et al. 1975); hence this has become a standard method of assessing auditory sensitivity in clinical audiology.

Using the head-orienting measure, studies with young infants have shown that the ability of infants to discriminate sounds to the right vs. left undergoes a steep maturational progression early in life. Summary of data from experiments described below is shown in Fig. 10.5a. MAA thresholds are near 25° at 2–4 months of age, decrease to approximately 10° by 6 months, and are as small as ~5° by 18 months of age (see Litovsky 1997). While MAA thresholds continue to mature into childhood, reaching 1° by 5 years of age, the 5° thresholds at 18 months suggest that young toddlers have a well-developed skill regarding discrimination of spatial cues at a prelingual stage in development. Studies described thus far used fixed-level stimuli, and it is possible that monaural level cues were available to the children. Thus, more recent studies have tried to minimize or eliminate overall level cues at each ear by roving the levels; thus the listener could solve the task by comparing the level cues at the two ears. Grieco-Calub et al. (2008) reported MAA thresholds near 10° for 2.5-year-old toddlers, and obtained slightly higher thresholds averaging 14.5° in a later study (Grieco-Calub and

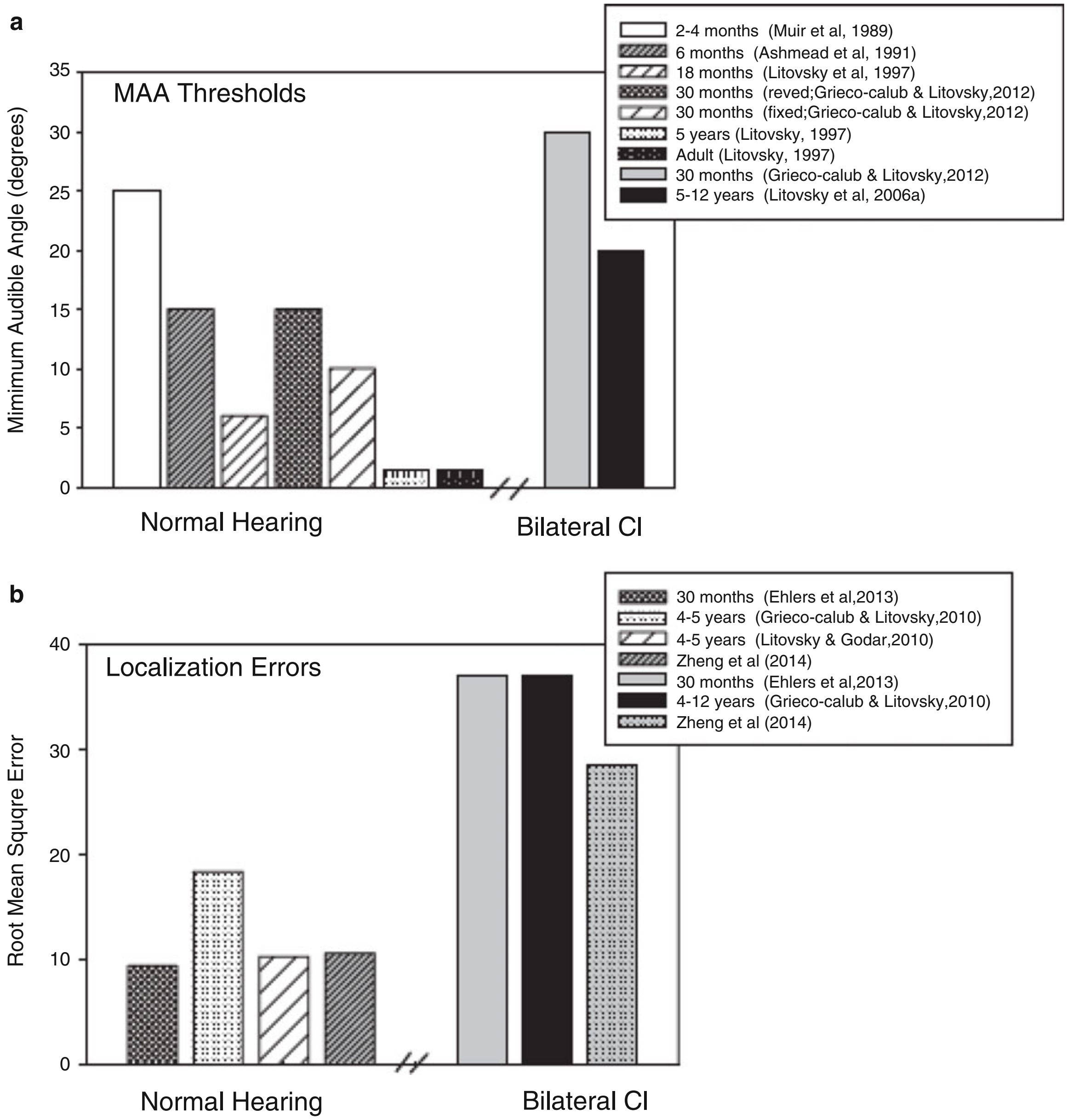

Fig. 10.5 (**a**) Summary data of minimum audible angle (MAA) thresholds are shown from a number of studies. (**b**) Summary data of root-mean-square (RMS) errors from localization measures are shown from a number of studies. With kind permission from Springer Science and Business Media (Litovsky 2011b)

Litovsky 2012). Thus, in young children with NH, localization acuity undergoes considerable maturation during the first 5 years of life, and the acuity of performance depends on the task and stimuli. During this time of life when the auditory system undergoes considerable maturation, there is an important interplay between the auditory inputs that are available to the children, the integrity with which the auditory system can process the information, and the ability of the listener to utilize those cues on everyday listening tasks.

In children who are deaf and who receive bilateral CIs, the ability to extract information regarding source locations to the right vs. left is complicated by the fact that they are typically not implanted in both ears until about 1 year of age; some children receive both CIs before a year of age, while other children are several years old at the time of the second implantation. The clinical practice regarding this issue varies and is beyond the scope of this chapter. Needless to say, there are many complications that are involved in determining the success of bilaterally implanted children, and some of the limitations known to us to date are included in Table 10.1. In some ways, it is quite remarkable that bilaterally implanted children are able to localize at all, and that some of the children perform at levels that are within the performance levels observed in the normal hearing population. Summary of the data from bilaterally implanted children is shown in Fig. 10.5a, alongside the summary of results from NH children. Grieco-Calub and Litovsky (2012) tested 27 toddlers with an average age of 2.5 years, who received their second CI by 18 months of age. The MAA thresholds ranged from 5.7 to 69.6° (mean 31°). Unilaterally implanted toddlers were unable to perform the task, and the bilateral group was unable to perform the task if one of the CIs was removed, providing evidence for the use of a second CI when children discriminate sounds that are presented from the right vs. left. From an ecological standpoint, an average of 31° discrimination would provide these children with ample cues to know whether a sound of interest (voice, vehicle, etc.) is on their right or left. From a neuroscience perspective, the issue is more to do with the acuity of the neural mechanisms involved, and here there is a clear gap between the NH and bilateral CI groups. It is quite interesting that 5/27 toddlers tested had MAA thresholds within the range observed for the NH group, and all had more than 12 months of bilateral listening experience. Thus the role of auditory experience in the bilateral CI group might be an important factor in considering emergence of spatial hearing skills.

The head-orienting task, used for studies described thus far, has one potential flaw in relation to toddlers: a lack of ecologically interesting testing engagement. The reinforcement provided is at times boring and thus potentially questionable regarding the children's interest in the task. The variability observed within study and across studies may be due to this issue. More recently Litovsky and colleagues have developed and implemented a more ecologically interesting task for toddlers, whereby the task is to reach for a sounding object that is hidden behind a curtain (see earlier in chapter for description). The Reaching for Sound (RFS) method has proven to be fruitful with both NH children and subjects who are implanted with CIs. The RFS method was inspired by studies on "reaching in the dark" with NH infants, showing that sound location can be identified as early as 6 months of age based on auditory cues alone (Perris and Clifton 1988). In addition, at 6 months of age NH infants use their reaching behavior to indicate that they can discriminate sound source distance, and that they are not using intensity cues to solve the problem (Litovsky and Clifton 1992). This work is reviewed in more detail by Litovsky (2011a, b). In the CI population, the reaching behavior was motivated by testing in the light, for hidden objects that the child is motivated to find. Litovsky et al. (2013) tested bilaterally implanted toddlers with source locations at ±60°, ±45°, ±30°, or ±15°. First, discrimination was conducted for each of these location pairs, when listening bilaterally or with a single CI. As shown in Fig. 10.6, all toddlers were able to perform the task when using both CIs, and unilateral CI use was poorer. These results suggest that the RFS method is quite useful for yielding good performance from all toddlers tested, and that as reported above, bilateral CI use produces better results than unilateral CI use.

The MAA studies with bilaterally implanted children actually began prior to the toddler studies. Litovsky et al. (2006a) studied children ages 3.5–6 years and found that compared with unilateral listening conditions, bilateral listening provided an advantage for right vs. left discrimination. With both CIs activated, 9/13 children tested were able to perform the MAA task above chance, and the majority of the children demonstrated MAAs that were at least as good as 20°. Thus, the best-performing children demonstrated thresholds in the range of those observed with infants or toddlers with NH, who had similar hearing ages to the CI users. Also notable is the finding that of the nine children who had good MAAs, eight showed performance that was superior to the performance observed with one of the CIs turned off. The other 4/13 could not perform the right vs. left discrimination task; and "appeared to have little understanding of the fact that sounds can carry information regarding spatial location" (Litovsky et al. 2006a). The factors listed in Table 10.1 are considered to be highly relevant here in terms of the limitations contributing to the poor performance observed in these children. Notably, these children were older than the toddlers discussed above, both when they were tested and when they were bilaterally activated; the latter is most likely to be a cause of limitation. In a follow-up study, Godar and Litovsky (2010) focused on examining how MAA thresholds change over time, for children who are unilaterally implanted and transition to using bilateral CIs. Results were compared for intervals at the unilateral use stage, then at 3 months and 12 months following bilateral activation. For most children, MAA thresholds improved after transitioning to bilateral CI use, at 3 months, and even more so at 12 months after bilateral activation. More important, for these children, MAA thresholds remained poor, although that could have been due to the fact that they no longer received listening experience with a single CI on a daily basis.

Compared with sound location discrimination, sound localization taps an additional level of auditory perceptual processing, whereby auditory spatial mapping is involved, and localization perception is much more accurate than just hemifields discrimination. In addition, because localization involves the identification of the location of a sound source from amongst many options, this is a more difficult task than a 2-alternative forced-choice task used for the MAA measure. Initial studies with bilateral CI users were conducted with the same children who had been implanted with the second CI at relatively older ages (4–12 years of age). Comparison with NH children are quite important because the baseline needs to be well established as far as what the

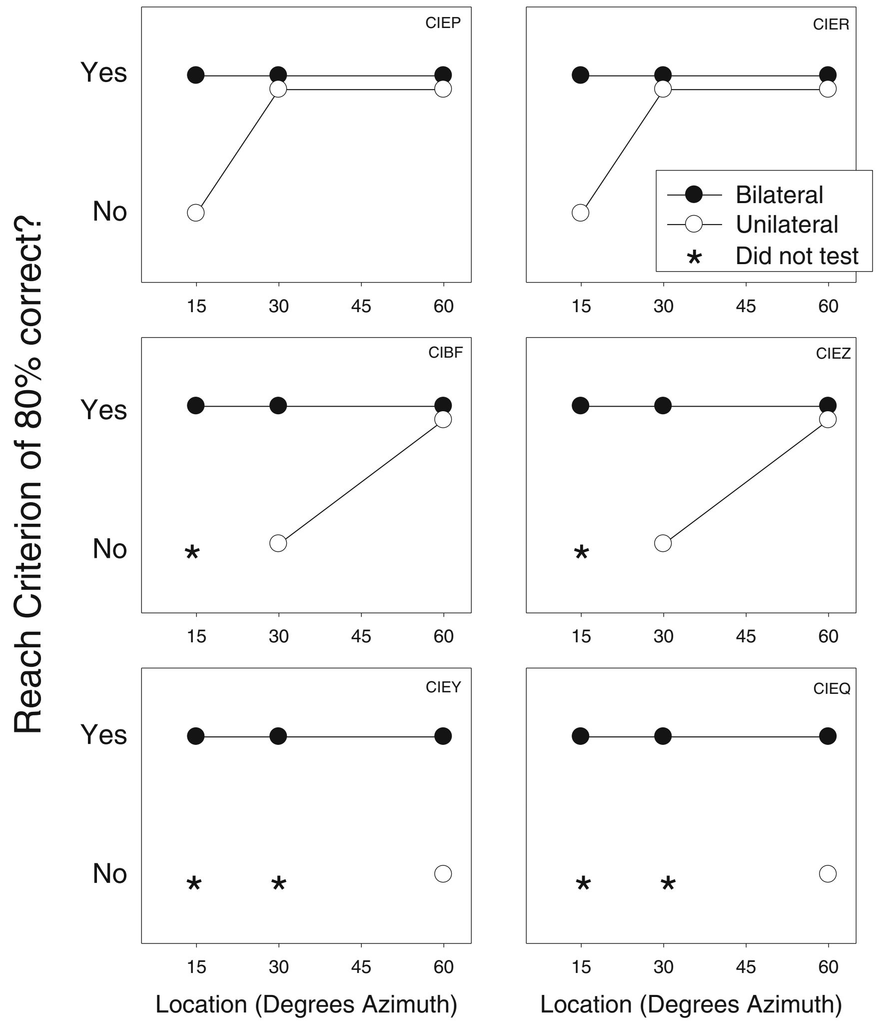

Fig. 10.6 Results from a study on spatial hearing using the "reaching for sound" paradigm are shown. Each panel shows data from a single child. The *x*-axis shows the locations used and the *y*-axis depicts whether the children passed a criterion of 80 % correct or not ("yes" or "no"). *Filled* and *open symbols* show results form bilateral and unilateral testing conditions, respectively. With permission from Litovsky et al. (2013)

expectation might be for emergence of spatial hearing in CI users. NH children ages 4–10 years show average error rates ranging from <5° to >30°. Root-mean-square (RMS) errors reported by Grieco-Calub and Litovsky (2010) were 9–29° (average of 18.3° ± 6.9° SD) in NH children ages 4–6 years old; note that <10° is within the range observed in NH adults. Two other studies reported smaller RMS errors of 1.4–38° (avg 10.2° ± 10.72° SD; Litovsky and Godar 2010) and 4–10° (Van Deun et al. 2009). These values overlapped with the RMS errors measured in NH adults. The RFS method described above was recently also adapted to measure sound location identification in toddlers, with a task requiring them to select one of nine locations as the perceived location of the sound source. Most of these toddlers were able to identify locations correctly on >95 % of trials (RMS errors <10°), and a small group of 2.5-year-olds selected the incorrect locations more frequently (RMS errors near 30°). Figure 10.5b shows average RMS from this and numerous other studies, for NH and bilateral CI users.

In bilateral CI users, sound localization studies were initially conducted with children who had very little experience listening with their CIs, and who were ages 4–12 at the time of activation of bilateral hearing. Litovsky et al. (2004) reported that RMS errors were near chance (~55°) after 3 months of bilateral CI users, suggesting poorly developed spatial hearing skills. Later studies investigated children with greater amount of listening experience, with notable improvement for some children. Grieco-Calub and Litovsky (2010) reported RMS values of 19–56° for spondaic speech stimuli; these values fell into a similar range of RMS errors (13–63°) reported by Van Deun et al. (2010) who used a broadband bell ring as the stimulus. Interestingly, using the RFS methodology, Ehlers et al.'s (2013) preliminary findings with toddlers show average RMS errors of 37° (range 11–52°), which is well within the range observed with the older children. The difference might be due to the difference in number of loudspeakers (9 for toddlers and 15 for older children); however that is unlikely to be the primary explanation, because even with a 7-loudspeaker array some of the older children did not perform well on the localization task (Grieco-Calub and Litovsky 2010). Another possibility has to do with the exposure to bilateral hearing during early stages in development: the toddlers had been bilaterally implanted at a younger age than the children, and had more of an opportunity to become used to the bilateral cues and to use them on a sound localization

Speech Understanding in Noise and Related Phenomena

One of the overarching goals of providing bilateral CIs to young children is to enhance their ability to understand speech in everyday noisy listening situations. The question as to how to study the benefits from bilateral CIs compared with the use of a single CI led us to utilize the spatial release from masking (SRM) measure to evaluate sound source segregation abilities in these children. The key comparison in these studies is between conditions in which the target and masker(s) are co-located, and conditions in which they are spatially separated. Any improvement on the separated condition relative to the performance observed in the co-located condition is denoted as positive SRM; negative SRM refers to a disadvantage from spatial cues, which is seen at times in patients who use hearing aids or CIs. In NH adult listeners SRM can be as high as 12 dB improvement in the signal-to-noise ratio required to correctly identify the target speech; large SRM typically occurs when binaural cues are available, and when the target/maskers are similar or confusable (similar voices; Durlach et al. 2003; Jones and Litovsky 2008, 2011). The magnitude of SRM is also thought to be divided into both monaural and binaural and components (Hawley et al. 2004). Bilateral CI users are typically able to benefit from monaural-driven SRM, but have little access to the binaural cues that provide additional benefits for source segregation based on binaural cues.

Studies on NH children began about a decade ago. Litovsky (2005) first demonstrated SRM in NH children ages 4–7, using target stimuli consisting of spondaic words, and maskers that were either temporally modulated speech shaped noise or sentences spoken by a different-sex talker from the targets. Targets were presented from the front at 0°, and maskers were presented from locations that were either co-located with the target or spatially separated from the target. Using a novel 4-alternative forced-choice (4AFC) task, children indicated which target word they heard. Litovsky (2005) reported SRM values of 5–7 dB. In fact, SRM values were higher with two maskers (7.4 dB) than with a single masker (5.2 dB), indicating that the more complex auditory environments promote larger benefit from spatially separating potentially interfering sounds from the source of interest. Two further studies demonstrated that SRM is well developed at young ages. Garadat and Litovsky (2007) pursued this line of investigation in 3–4-year-old children, and reported similar, or slightly higher SRM values for that population, suggesting that the ability to use spatial cues to segregate target speech from maskers is developed by 3 years of age. Most recently, Hess CL. Speech discrimination and spatial hearing in toddlers with bilateral cochlear implants. Unpublished PhD Dissertation and University of Wisconsin-Madison (2013) measured SRM in toddlers, and found that the effect was fairly mature by 2.5 years of age. In those two studies, SRM was only evaluated for the conditions with maskers displaced asymmetrically around the head (see Fig. 10.4c); thus the “head shadow” might have been a highly dependable cue, and the extent to which binaural cues were used was not clear.

The first study with bilaterally implanted children was by Litovsky et al. (2006b) who used a similar design and stimuli as described thus far. The masker locations however were varied so that they were towards the side of either the first CI or the second CI. Results were compared with those from a group of children who used bimodal hearing (a CI in one ear and hearing aid in the other ear). For many of the children, the fact that both ears received input meant that there was an advantage to hearing the target speech at lower levels (lower SRTs) than those obtained in the unilateral listening condition. However, there was large inter-subject variability for this effect. For spatially separated conditions, the bimodal children, on average, did not have SRM; rather they had a “binaural disruption” effect, such that SRTs were higher for the separated than for the co-located conditions. This might indicate that the bimodal users lacked the ability to integrate information from the two ears in a way that benefited their source segregation. Other studies on similar measures with bimodal fitted children have not reported a similar disruptive effect (e.g., Ching et al. 2005, 2006). The differences, which should be further explored, might be due to variation in amplification approaches, different amounts of residual hearing in the unimplanted ear of the Ching et al. studies. In contrast with the bimodally fitted children, the bilateral CI users, on average, showed SRM that fell into the range observed in NH children. However, the effect was larger when the maskers were near the second CI than when they were near the first CI.

A more systematic evaluation of SRM was conducted by Misurelli and Litovsky (2012) who tested children ages 4–6 and 7–9 on similar tasks, with the added condition shown in Fig. 10.4d, whereby the maskers were symmetrically placed to the right and left, minimizing or eliminating the better-ear “head shadow” cue. In the NH groups, children were still able to demonstrate SRM in the symmetrical condition, although the values were smaller than with the asymmetrical condition. In the bilateral CI groups, SRM was achieved in both age groups with asymmetrical maskers, but was very difficult to achieve with symmetrical maskers. Here again the contribution of monaural head shadow to spatial separation of target speech from maskers seems to be an important contributing factor.

Conclusions

Young children are fitted with hearing aids and/or CIs so that language acquisition and verbal communication can be developed, ideally at age-appropriate levels. CIs were designed to provide the signal processing necessary for stimulating the auditory nerve so that patients could hear speech, in quiet and in noise. For children, the goal was to provide each individual with the skills needed to function in a mainstreamed auditory environment. Bilateral CIs were not designed in a way that mimics the binaural system's ability to compute source locations and to squelch noise or reverberation based on interaural comparisons. Thus, to the extent that children who are bilaterally implanted show benefits from two CIs reflects the ability to their brain to interpret the signals from the two ears using rudimentary processing of binaural information. The studies that were reviewed here primarily focus on work conducted by Litovsky and colleagues, where parallel work is conducted in children with NH and with CIs. It is clear that, on average, bilaterally implanted children have a gap in performance relative to their NH peers. However, in many cases, the bilateral CI users' performance falls within the range of performance observed in the NH groups. That does not mean that the CI users are "the same" as the NH children, but it does mean that they are capable of resolving complex information about source location on the tasks that were described here. Many practitioners are concerned with being able to identify the age at which bilateral implantation will result in maximal recovery of function and minimal loss of auditory system integrity. The answer depends on numerous factors that can vary across individuals. Many of these factors were highlighted in Table 10.1. Future work will ideally focus on providing better understanding of how auditory system degeneration can be overcome, both peripherally and centrally. Because central mechanisms are thought to be more amenable to change following stimulation, stimulus-dependent learning and training can play an important role in habilitation.

Acknowledgments The author is very grateful to students, postdoctoral fellows, and collaborators whose participation in the cited studies was important to the success of this chapter, and to the research participants for their dedication to the understanding of bilateral and binaural hearing in children. The author received support for her work from the National Institutes of Health (R01 DC 003083 and 5R01 DC 008365).

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