Chapter Two

Development of Binaural Audition and Predictions for Real-World Environments

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Introduction

Children spend a majority of their time in environments containing multiple sound sources and abundant reflective surfaces. The auditory system is thus faced with continuously resolving competition for perception and localization between a source and noise or echoes. This competition is important to resolve in order to enhance abilities such as localizing sounds, understanding speech in noise, and suppressing echoes. The binaural system is known to play an important role in these three functions. In considering the developmental progression of binaural abilities, several questions come to mind: 1) How do young listeners compare with adults? 2) What is the developmental progression of binaural abilities? 3) What role do experience and early exposure play? 4) What benefit might hearing-impaired children gain from bilateral amplification?

Most research in this area has been conducted on questions 1 and 2, focusing on basic auditory mechanisms. Relatively little is known about questions 3 and 4. This chapter will highlight some findings that address these questions, and attempt to provide a framework for evaluating benefits afforded by bilateral stimulation with hearing aids, cochlear implants, or one of each.

Finally, prior to describing what is known about development of binaural hearing, it is important to note that interpretation of these results must be made cautiously and diligently. When attempting to understand sensory processes we are faced with the difficulty of insuring, to the best of our ability, that behavioral responses of the listener provide meaningful information regarding their perceptual experience. Since we cannot probe the neural circuits directly, we resort to indirect measurements and must rely on rigorous psychophysical techniques. While these methods have been worked out in detail for adults, their extrapolation to pediatric population must be conducted with great care. Unlike adults, who can provide verbal feedback about their sensory experience, young listeners lack that mode of communication. Hence, we are faced with measuring behavioral responses to stimuli and interpreting those behaviors. Over the years, numerous scientists have measured responses to auditory stimuli in infants and have greatly enhanced our understanding of the auditory system. Extensive reviews on the methods, theories attached to them, and other developmental psychoacoustic issues are available in a book edited by Werner and Rubel (1992).

Binaural Cues

The ability to localize sound sources requires the use of remarkably precise auditory cues. While the most reliable cues used in spatial hearing arise from the comparison of the signals reaching the two ears, listeners also utilize cues that arise from monaural (one-eared) processing. Consider a sinusoidal sound source presented in the horizontal plane on the left side of the head (see figure 1). The sound reaches both ears, however when it arrives at the farther ear it is delayed in time and attenuated relative to its arrival at the nearer ear. There are thus two important cues for directional hearing: inter-aural differences in time (ITDs) and intensity (IIDs). However, due to the physical laws by which sound waves interact with objects, ITDs and IIDs are not equally important at all frequencies. High frequency sounds have relatively

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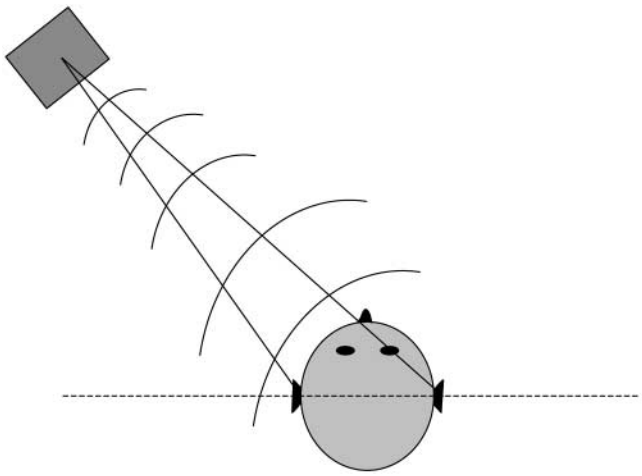

Figure 1. A depiction of sound waves emanating from a source in free field to the left of the listener's head. Sound waves reach the left ear first, followed by the right ear, creating an inter-aural difference in time (ITD). This difference is maximal for sounds that have a low frequency, since the auditory system can resolve the temporal differences between those waves. In addition to ITDs, there is an inter-aural difference in intensity (IID), since the sound is attenuated by the head and reaches the near (left) ear with greater intensity than the right ear. This binaural cue is greater for high frequencies, which do not "travel around" the head as readily as low-frequency sounds do, and are therefore more susceptible to being attenuated.

short wavelength compared with the head, thus they are "shadowed" or attenuated by the head, providing IIDs as large as 20 dB for sounds at 90 degrees on the side. Low frequency sounds on the other hand, have longer wavelengths, causing them to "bend" around the head and to be diffracted, resulting in lack of shadowing. Although, low frequency sounds do provide robust ITDs, as large as 700 µs for sounds at 90 degrees to one side. Over the years, numerous studies have been conducted on listeners' abilities to extract binaural cues from sound sources, providing a measure of the integrity of the binaural system.

Auditory Localization

Auditory localization is a fundamental ability that enables most animals to identify where important sources in the environment emanate from. In humans, the development of this ability has received attention in the past couple of decades, with convincing evidence that newborn infants orient their heads towards sounds within hours after birth. This finding was first documented by Muir and Field (1979) and soon thereafter confirmed by Clifton, Morrongiello, Kulig and Dowd (1981). In these studies, the infant's head is held in the palm of the experimenter who wears masking headphones, to avoid potential cueing of the infant in any manner. Prerecorded rattle sounds were presented from loudspeakers at 90 degrees to the right or left, or above the infant (see figure 2a for method description). The proportion of trials on which head turns toward the hemifield containing the sound source occurred was recorded (see table 1). Although the head turning does not occur on every trial, when it occurs the response is towards the correct hemifield, suggesting that already at birth human infants can orient towards a

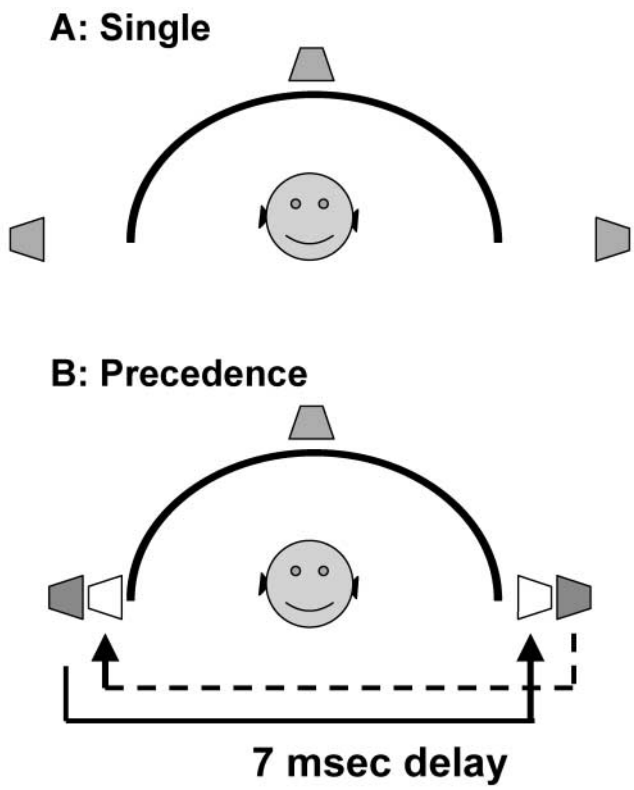

Figure 2. Methodology for testing newborn head turning responses is shown. (A): On single source conditions speakers were positioned to the infant's right, left, or overhead. On each trial, a single source sound was emitted from one of the speakers, resulting in three types of trials. (B) On precedence conditions speakers were positioned in the same arrangement. There are also three types of trials, with the overhead (control) one being the same as in A. On the other two trial types two identical sources are emitted, with one being delayed relative to the other. On one trial type the right speaker leads the left, and on the other trial type the left speaker leads the right (from Clifton et al.1981).

Table 1. The proportion of trials on which infants turned their heads towards sounds, away from them or did not initiate a head turn, are compared for newborns and 5-month olds (columns), for single-source or precedence conditions.

	Newborn	5-months
Single		
Toward	53	47
Away	10	0
No turn	48	69
Precedence		
Toward	8	45
Away	9	0
No turn	90	68

sound source. Note however, that this response is unconditioned and therefore quickly extinguished, hence only a handful of trials are usually available from any given infant. In addition, it has a fairly long latency of 8 seconds or more. Additional difficulties in conducting this work arise from the fact that the head turn response only occurs when the infant is in an awake and non-fussy state, which is not common in newborn infants. Nonetheless, as the results shown in table 1 suggest, within hours after birth, a normal-hearing infant will orient toward the correct hemifield containing a sound source reliably, and virtually all responses are accurate.

The development of sound localization begins at birth and continues throughout infancy and childhood. In fact, while some basic abilities reach adult levels of performance during the preschool years, most abilities do not, and continue to undergo changes during school age. One of the most striking aspects of the early development of sound localization is illustrated by the non-monotonic head turning response. Although beautifully elicited at birth, the response seems to "disappear" from about 1–3 months of age, and to reappear at around 4 months of age (Field, Muir, Pilon, Sinclair and Dodwell 1980; Muir, Clifton and Clarkson 1989). At this age, head turning towards sound has matured into a conditioned head turn with a latency of 1 second or less, much more brisk and "intentional" than that of newborns. Although the mechanisms for this change are not well understood, a prevailing hypothesis suggests that the neonatal response is reflexive and most likely mediated by "lower" brainstem circuits. In contrast, the response at 4 months and older is most likely mediated by "higher" circuits (perhaps cortical) that have matured to some extent during the first few months of life (Clifton 1985). This hypothesis is consistent with the fact that at 4–5 months of age head turning responses can be used in discrimination learning paradigms such as visual reinforcement audiometry (VRA; Moore, Thompson and Thompson 1975). In this technique, infants are trained to turn their heads in a direction consistent with a perceived change in an attribute of the sound being measured, and they are reinforced with attractively activated toys.

Ultimately we would like to know *where* infants perceive sound sources to be, and the extent that they can accurately do so. In adults this is not a trivial task, although several investigators have, over the years, developed rigorous methods for obtaining reliable and consistent measures from verbal reports (e.g. Wightman and Kistler 1989), or accuracy of head orientation to the target (Makous and Middlebrooks 1990). Young infants cannot provide verbal feedback, and using head orientation or other motor responses to measure accuracy will always leave us wondering whether "inaccuracy" reflects immaturity of the auditory system, the motor system, or the translation of sensation to a behavioral response.

Minimum Audible Angle

An alternate approach used to study the developmental progression of sound localization in human infants is the minimum audible angle task (MAA), measuring the smallest change in the position of a sound source that can be reliably discriminated. The beauty of this task is that VRA can be used to measure responses in a dichotomous format, in which two response options are available (i.e., head turn vs. no head turn, or head turn towards the right versus left). Hence, other than requiring a simple discrimination between two options, the VRA avoids the need for a precise motor response. While the relationship between MAA and sound localization is not well understood, it is clear that the MAA provides a measure of the *limit* of the binaural system and can be used to chart infants' ability to extract information from sound sources presented in free field. This method is illustrated in figure 3. A trial begins by presenting an attractive toy in front of the infant to center the infant's head. A sound source is then

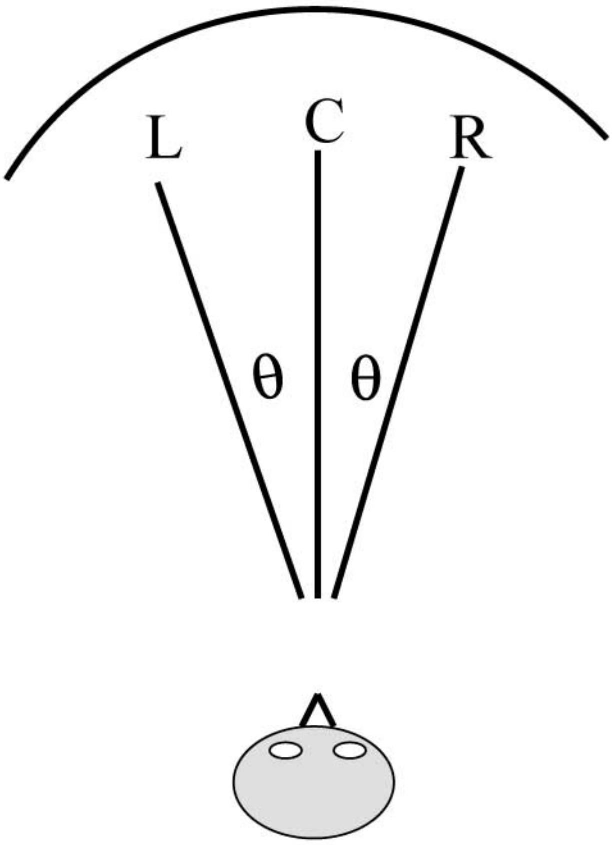

Figure 3. Methodology for Minimum Audible Angle (MAA) testing is shown. Three loudspeakers are positioned, with one in front of the listener (C, center) and two others to the right and left at identical spatial separations from the center. On each trial a sound is emitted from the center, and once the infant's head is oriented in that direction the sound shifts either to the right or left. Following a head turn in the correct direction, a visual reinforcer is activated on that same side, and following an incorrect head turn or no head turn there is a "time out" period of a few seconds. The spatial separation of the loudspeakers can be varied either adaptively (e.g., Litovsky 1997), or randomly (e.g., Morrongiello 1988).

played from a loudspeaker in the center location, and abruptly switches either to the right or left of that location. The right and left sides are chosen randomly from trial to trial. On each trial, the infant is expected to turn her/his head if a change in the sound source position is perceived. Most infants do so readily, since they are trained to expect a reward following a head turn in the correct direction. The angular separation between the sources can be varied adaptively, by increasing or decreasing the separation, depending on whether the response was correct or incorrect. A set of rules are applied which determine when the angle is increased or decreased, by how much, and at what point testing should be terminated. MAA threshold is then calculated by averaging specific angle values during a series of trials (for a detailed description of this method see Litovsky and Macmillan 1994; Litovsky 1997). Alternatively, the angular separations can be selected ahead of time, and a given number of trials presented at each one. Percent correct at each location is then plotted, and MAA threshold is estimated from a psychometric function by finding the separation corresponding to 71% correct. In both cases, the infant's response is scored by an observer who is "blind" as to the trial type.

During infancy there is a dramatic developmental change in the MAA, shown in figure 4. While MAA is about 20° to 25° at 4 months, it decreases to less than 5° by 18 to 24 months (Ashmead, Clifton and Perris 1987; Ashmead, Davis, Whalen and Odom 1991; Litovsky 1997; Morrongiello 1988; Morrongiello and Rocca 1990), and reaches adult maturity of 1° by 5 years of age (Litovsky 1997). A handful of studies on this topic suggest that ITD discrimination under headphones in infants as young as 4 months is around 50–75 µs, which correspond to an MAA smaller than that actually measured (e.g., Ashmead et al. 1991). This disparity between ITD thresholds and MAA may imply that sensitivity to the binaural

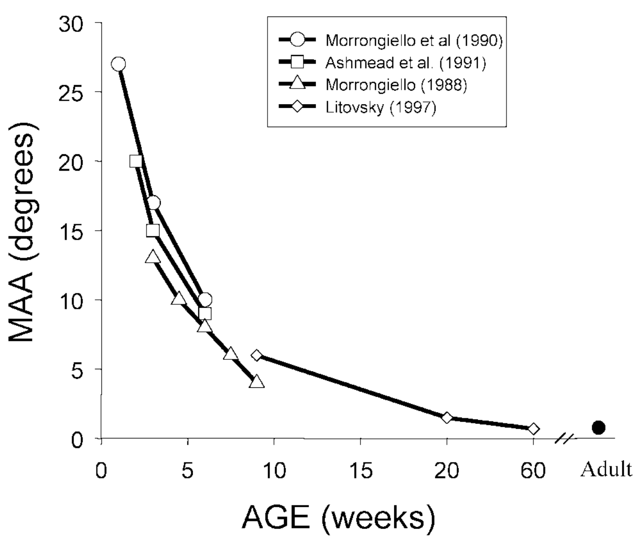

Figure 4. Developmental trend in Minimum Audible Angle (MAA) thresholds is shown, with data from four different studies covering the range of 1 month to 5 years. MAA thresholds are plotted as a function of age in months, and adult data are shown at the right end of the plot.

cues per se is well developed early on during development, and that the translation to real-world sounds may take longer to develop. An important caveat to this work is that while the MAA and ITD/IID discrimination are instructive regarding the limits of the auditory system, they do not necessarily provide information regarding sound localization accuracy, which can only be attained by measuring a listener's ability to identify the actual location of sound source. Due to behavioral measurement problems mentioned above, little is known about true localization abilities in young listeners.

Distance Perception

Sound localization is inherently a three-dimensional process, since we experience sounds not only in the horizontal and vertical dimensions but also in distance. Despite the importance of our ability to judge the distance of sounds, our understanding of the localization cues that are important for this ability are relatively poorly understood (e.g., Ashmead, Davis and Northington 1995; Little, Mershon and Cox 1992; Shaw, McGowan and Turvey 1991). For developmental studies on this topic we have the added challenge of coming up with a behavioral measure that can be reliably used to indicate something meaningful about an infant's perception of an auditory object's distance. As all parents and caregivers of infants know, typically developing infants begin to reach for and grasp objects around them at around 5–6 months of age, bringing them to the mouth for exploration and manipulation. A number of studies on visual depth perception have shown that infants can discriminate between objects that are *within* versus *beyond* their reach (for review, see Yonas and Granrund 1985). Essentially, they show this discrimination by only attempting to grasp objects that are within their reach and not those beyond their reach.

This instinctive behavior in young infants was exploited in studies on auditory depth perception by measuring infants' reaching behavior for sounding objects in the dark (behaviors are observed/videotaped using infrared light). Perris and Clifton (1988) were the first to demonstrate that infants actually reach for sounds in the dark, and they do so fairly accurately in the horizontal dimension. Clifton, Perris and Bullinger (1991) further demonstrated that in the dark infants can rely on auditory information alone to make a dichotomous discrimination between sounding objects that are within their reach (10 cm) and not those beyond their reach (100 cm), since they mostly attempt to grasp those that are nearby.

Litovsky and Clifton (1992) focused on the question of which distance cue might be utilized to make this discrimination. They manipulated intensity, which varies inversely with distance (near sounds are loud and far sounds are soft), with a change of approximately 6 dB for every doubling or halving of distance. In this study, sounds at the near and far positions had a natural difference of 7 dB in intensity. Unknown to the subjects, sound pressure from the source could be manipulated to simulate different distances. Adult subjects tested by obtaining verbal responses showed a strong bias toward reporting that "soft" sounds were far and "loud" sounds were near, regardless of actual distance. Curiously, infants reached accurately for sounds regardless of distance. In contrast, adult subjects judged the louder object to be near and the softer object to be far, regardless of the actual distance. That is, they misused the information, relying on sound pressure level to judge distance, even when it was incorrect. Because infants do not seem to rely on sound intensity as strongly as adults do for distance judgment, it is likely that considerable experience-dependent development takes place during the early years.

The Precedence Effect

The precedence effect refers to a group of auditory phenomena that are important in our ability to function in reverberant environments. Studies on precedence simulate a simplistic reverberant environment by presenting two sounds from different directions, and delaying the onset of one relative to the other by a few milliseconds, not unlike a single echo occurring in a room. Studies on adults have measured various phenomena, including the extent to which the first and second source are fused, the extent to which the first sound dominates the perceived location of the echo, and the extent to which listeners are able to extract binaural cues from the echo (for review, see Blauert 1997; Litovsky, Colburn, Yost and Guzman 1999). In short, the echo is "suppressed" by the auditory system when the delay between the first and second sounds is short, and suppression decreases as the delay is increased. Hence, at short delays listeners hear one fused sound, whose location appears to be near the leading sound, and they cannot extract binaural cues from the echo.

Studies on precedence in young listeners suggest that it does not appear to be present during early infancy. Using the same paradigm as for the single-source head orienting experiments described above (see figure 2b), Clifton and colleagues (Clifton et al. 1981; Clifton 1985) presented newborn infants with pairs of sounds whereby the onset of one was delayed relative to the onset of the other by 7 milliseconds. They predicted that if infants demonstrate the precedence effect (i.e., suppress information from echoes), they should turn their heads towards the leading sound in the same way that they did towards the single source sound. At birth, infants did not orient their heads towards the leading source, suggesting that they were incapable of suppressing directional information from the lagging sound (echo). By 4–5 months of age infants demonstrated both the single-source and precedence head turning responses, suggesting that the mechanisms involved in negotiating echoes in complex acoustic environments begin to develop within the first half of the first year of life.

Not all aspects of echo suppression are fully developed in infancy however, nor by early childhood, and the maturational progression depends greatly on which aspect of the precedence effect is tested. For instance, while orientation to the correct hemifield containing the leading source is observed by 4–5 months, an infant's ability to detect the echo is quite different from that of children or adults. One measure of the strength of echo suppression is the delay between onset of the lead and lag at which the two sounds are no longer fused and are both heard at their respective locations, suggesting that the echo is no longer suppressed. This aspect of precedence is known as fusion, and the threshold values for click stimuli are 5–9 ms for adults and 5-year old children, compared with 25 ms for 6-month old infants. For click stimuli, which are relatively simple and have a short duration, children and adults show similar thresholds. In contrast, for more complex stimuli of longer durations, such a rattle sound, 5-year olds thresholds (30 ms) are higher than adults' (25 ms) (for review, see Clifton 1985; Litovsky and Ashmead 1997).

Another aspect of the precedence effect, discrimination suppression, refers to the observation that at short delays stimulus parameters of the echo are less discriminable due to the presence of the lead stimulus, and this ability improves as the delays increase, presumably due to reduction in suppression of directional information contained in the echo. Discrimination suppression also undergoes significant developmental changes during early childhood. Litovsky (1997) used the MAA paradigm to measure thresholds for the leading source (in the presence of the lag at midline; figure 5a), for the lagging source (in the presence of the lead at midline; figure 5b), and for a single source, at ages 18 months, 5 years, and adult. The stimuli were 25-ms noise bursts, and the lead-lag delay was 5 ms. Since this lead-lag delay is below the echo threshold for these stimuli, only one fused sound image is heard. Results are shown in figure 6. Single-source MAAs are adult-like (1° to 2°) at 5-years of age and fairly low (5°) by 18-months of age. Lead MAAs are quite low in adults (1.7°), somewhat elevated in 5-year-olds (4.4°) and substantially higher in 18-month-olds (23°). Lag MAAs are still low in adults (1.7°), but substantially higher in 5-year-olds (27.5°) and 18-month-olds (65°). Lead MAAs reflect listeners' ability to focus on the first-arriving wave-

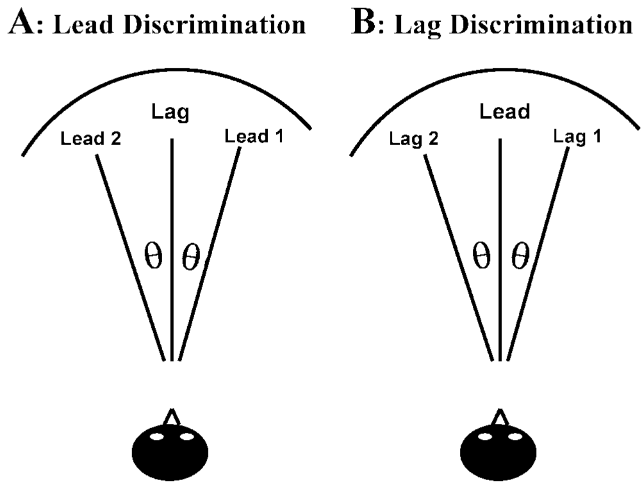

Figure 5. Methodology for applying the MAA paradigm to the precedence effect is shown. There are two trial types, and both begin with a single source sound presented from the center speaker. A: In lead discrimination, once the child's head is oriented towards the center, the stimulus changes to one containing two sources with the echo (lag) presented from the center speaker and the source (lead) presented from the right or left. The angular separation of the lead from the center is varied adaptively. B: In lag discrimination, once the child's head is oriented towards the center, the stimulus changes to one containing two sources with the lead from the center speaker and the echo (lag) presented from the right or left. The angular separation of the lag from the center is varied adaptively (from Litovsky 1997).

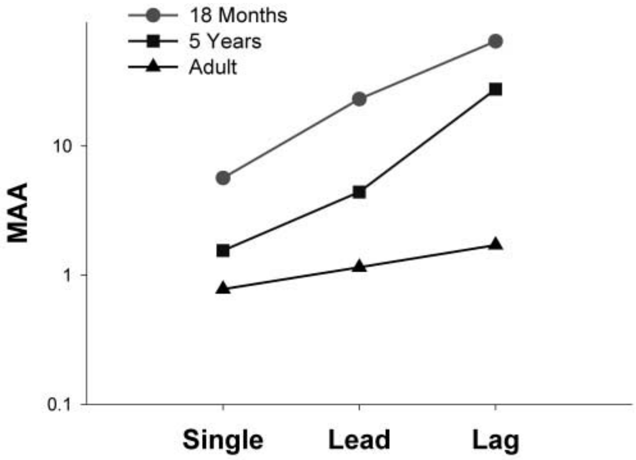

Figure 6. Minimum Audible Angle thresholds at 18 months, 5 years and adult are plotted for three stimulus conditions: single source, lead discrimination and lag discrimination (after Litovsky 1997).

front and to discriminate between leading source locations in the presence of the lagging source, and this ability improves dramatically with age. Lag MAAs reflect listeners' ability to extract directional information from a sound that is not heard as a separate auditory event; this ability improves somewhat with age but is still quite underdeveloped at 5 years relative to adults. These findings are consistent with the fusion echo threshold data, which were obtained using a task that measures children's ability to localize the lag as a separate sound. In the MAA study, normalizing the lead and lag results by the single-source results maintained the developmental differences observed, suggesting that lead and lag MAAs are not merely the "by-product" of a "noisy" single-source discrimination ability. As Litovsky (1997) points out, while the developmental work may point to maturational changes in the central auditory pathway, attentional and learning processes cannot be ruled out.

Finally, Burnham, Taplin, Henderson-Smart, Earnshaw-Brown and O'Grady (1993) suggested that echo thresholds also change developmentally as a function of maturation from time of conception rather than experience from birth. They reported that thresholds of pre-term infants were more similar to those of full-term infants matched for conceptual age rather than those matched for age since birth.

Taken together, work on development of the precedence effect suggests that in everyday listening situations, which are complex, full of competing echoes and other signals, infants and young children might have more difficulty processing relevant sounds. Their auditory system, being less developed and having had less experience, is not as capable as that of adults at negotiating competition between multiple sounds, suppressing irrelevant signals, and focusing more directly on the important "target" signals. In fact, it has been shown that children's speech comprehension (Neuman and Hochberg 1983) and sound localization abilities (Besing and Koehnke 1995) are diminished in a reverberant environment. Surely, if that is the case for children and infants with typical "normal" hearing, one might predict that young listeners whose auditory system has been compromised by sensori-neural or conductive hearing loss would also have difficulty functioning in complex environments. In fact, studies conducted on children with a long history of otitis media with effusion suggest that their ability to benefit from binaural cues is diminished compared with that of children with a negative history (Besing and Koehnke 1995; Hall and Gross 1993; Moore, Hutchings and Meyer 1991). In these studies, binaural masking level differences is measured over headphones. Here, the listener's ability to detect a tone in noise is compared when both tone and noise have the same ITD, hence heard in the middle of the head, or when an inter-aural phase difference is imposed in the tone, producing a noise that is heard in the middle of the head and a tone that is heard on the side. This perceived separation between the tone and noise results in improved ability to detect the tone in noise, referred to as the binaural masking level difference (BMLD). This measure might be useful in assessing the extent to which a child can extract simple binaural cues such as phase differences from sounds in the environment. The fact that children with OME show reduced BMLD suggests that their binaural ability is compromised, which leads one to wonder the extent to which children with permanent hearing loss would show similar effects. These studies have not been conducted, but would certainly be quite important.

Speech Intelligibility in Noise and Spatial Release from Masking

While important and interesting, the BMLD studies were conducted under somewhat non-realistic environments in which ITDs were the only cues available for separating the signal from masker. As was discussed earlier in the chapter, in free field, changes in sound source location result in binaural cues such as ITDs and IIDs, as well as monaural cues due to shadowing of sounds by the head. Recent work in our laboratory (Litovsky, Dalal and Ng 2001) has focused on developing a new paradigm for investigating children's ability to function in complex acoustic environments. The aims of this work are twofold. First, we can broaden our understanding of developmental changes in complex binaural abilities. Second, by simulating realistic acoustic environments we may be able to predict how individual children might actually perform in the real world, in classrooms, playgrounds and crowded spaces, where they are faced with the challenge of overcoming competition from noisy sources. The ultimate goal of this research is to understand how young children are able to separate out individual sources and to ignore what one person is saying in the presence of competing voices. This problem is commonly known as the "cocktail party problem," "sound source determination" or "sound source segregation." (e.g., Bregman 1990; Yost 1997). This problem has been studied extensively in adults, with and without hearing impairment. Recent research in adults (e.g., Hawley, Litovsky and Colburn 1999) has shown that speech is significantly more intelligible when the "target" speech and competitor are spatially separated than when they are near one another, especially if binaural cues are available. This effect is called "spatial release from masking."

To study this effect in young children, Litovsky et al. (2001) developed a task that engages the child through an interactive game, making measurements in a large sound proof booth (see figure 7). The test involves a one-interval four-alternative-forced-choice discrimination procedure, on which the child chooses a picture that matches the heard word and is reinforced following correct responses. Measurements are made under three conditions: (1) Quiet: the targets are presented from the frontal position with no competing sources, (2) Target/competitor overlap: the competing source(s) occur at the frontal location as well, (3) Target/competitor separated: the competing source(s) occur on 90° to the right and/or left. Speech-reception-threshold is measured adaptively, estimating 79% on the psychometric function. Figure 8 shows sample data from one child, with quiet thresholds in panel A and all three conditions in panel B. Note that in absence of a competing source, the child's speech reception threshold (SRT) is 22 dB SPL. When a competing speech sound is added at the same location as the target speech, SRT rises to 42 dB SPL. When the competing sound is placed 90° to the right of the target, there is a spatial release from masking, whereby SRT decreases to 31 dB SPL. Similar findings have been seen in numerous children, with some variability in the SRT values and amount of spatial release from masking, ranging from 3 to 12 dB. Rarely does a child fully "recover" from the effect of masking by returning to the quiet threshold when the competing sound is on the right. These findings are somewhat different from those found with adults. First, on this forced choice task adults are much better able to pick out the target, presumably using subtle linguistic cues, hence they have a much weaker masking effect. In addition, spatial separation of target and competitors results in complete release from masking and a return to the baseline quiet condition. Second, on a more difficult open set task using HINT sentences (not tested with children yet), adults show a maximum of 8 dB masking and 6–8 dB release from masking. Hence, the binaural advantage is one that adults are highly capable of utilizing. Preliminary data with children suggests

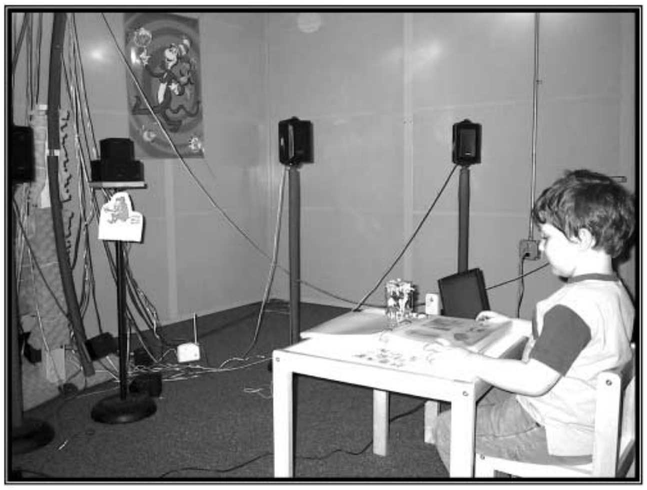

Figure 7. This figure demonstrates the room used for the experiments on spatial release from masking. We used a single-walled sound chamber with internal dimensions of 12' x 13', and reverberation time (T_{60}) of 250 ms. The child is seated in the center of an arc with a 5-foot radius. The angular separation of the target and competing sound can be varied, from none (both at center) to 180°. At the beginning of each trial the child is asked to face the center speaker prior to stimulus presentation.

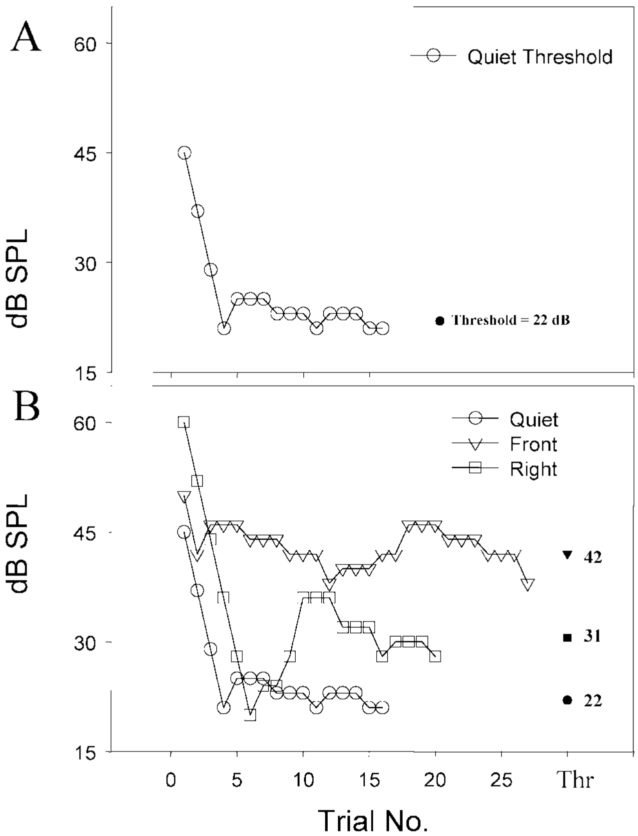

Figure 8. Sample data from the spatial release from masking data are shown for one child. Data are collected using an adaptive track. A: Adaptive track for the 'quiet' condition (○), resulting in a threshold of 22 dB. B: Adaptive track for the 'quiet' threshold (○) is replotted along with that for conditions with a competitor on the right (□) or in front (▽).

that their mechanism for operating in these complex environments may be quite different than the adults' and that further research is necessary in order to better understand these processes.

Clinical Implications

People with hearing impairment often complain that noisy environments are quite difficult to negotiate, and hearing aid manufacturers have been diligently working on improving noise-reducing algorithms that improve the signal-to-noise ratio afforded by amplification systems. Where children are concerned, interference from noise can be frustrating, can lead to reduced learning in the classroom and social isolation. In order to provide children with the best possible amplification system it might be worthwhile to test the viability of their hearing aid or cochlear implant under conditions that simulate realistic noisy environments, and determine the scenarios under which they function best.

Some of the tests described here might prove to be useful when assessing children's ability to function in complex environments. For instance, the MAA task (Litovsky 1997) provides an efficient means of establishing the extent to which an infant/child can extract spatial cues from sound sources. Under conditions of the precedence effect, the MAA task can be applied towards estimates of cortical maturation. It may also prove to be a useful measure in predicting a young listener's ability to cope with reverberant spaces, such as classrooms, cafeterias, etc. Finally, the SRM speech task (Litovsky et al. 2001) can be a useful predictor of auditory and verbal learning, especially for children who are mainstreamed in the school system. By using these measures in the clinic, we may be able to optimize programming of amplification devices such that they are helpful in both quiet and noisy situations.

Finally, one often wonders whether a child should be fitted with one or two devices (hearing aids and cochlear implants alike). Setting aside cost issues, in an ideal world hearing impaired individuals with bilateral loss should probably receive two devices. We know from the binaural hearing literature that listeners function significantly better under binaural than under monaural conditions. We also know from anecdotal and subjective reports that the world is a much more negotiable place when bilateral hearing is available. The tests described here are most likely the best predictors of binaural benefit. By using these measures in a reliable and consistent fashion, the clinician can gain insight into a child's needs and provide the most effective instrument(s) for each individual.

References

Ashmead, D.H., Clifton, R.K., and Perris, E.E. 1987. Precision of auditory localization in human infants. *Developmental Psychology* 23: 641–647.

Ashmead, D.H., Davis, D.L., and Northington, A. 1995. The contribution of listeners' approaching motion to auditory distance perception. *Journal of Experimental Psychology: Human Perception and Performance* 21: 239–256.

Ashmead, D.H., Davis, D.L., Whalen, T., and Odom, R.D. 1991. Sound localization and sensitivity to interaural time differences in human infants. *Child Development* 62: 1211–1226.

Besing, J., and Koehnke, J. 1995. A test of virtual auditory localization. *Ear and Hearing* 16: 220–229.

Blauert, J. 1997. Spatial hearing: The psychophysics of human sound localization. Revised ed. Cambridge, MA: The MIT Press.

Bregman, A. 1990. Auditory scene analysis. Cambridge, MA: The MIT Press.

Burnham, D., Taplin, J., Henderson-Smart, D., Earnshaw-Brown, L., and O'Grady, B. 1993. Maturation of precedence-effect thresholds: Full-term and preterm infants. *Infant Behavior and Development* 16: 213–232.

Clifton, R. K. 1985. The precedence effect: Its implications for developmental questions. In S. E. Trehub and B. Schneider (eds.), *Auditory development in infancy* (pp.85–99). New York: Plenum Corp.

Clifton, R. K., Morrongiello, B.A., Kulig, J.W., and Dowd, J. M. 1981. Newborns' orientation toward sound: Possible implications for cortical development. *Child Development* 52: 833–838.

Clifton, R.K., Perris, E.E., and Bullinger, A. 1991. Infants' perception of auditory space. *Developmental Psychology* 27: 187–197.

Field, J., Muir, D., Pilon, R., Sinclair, M., and Dodwell, P. 1980. Infants' orientation to lateral sounds from birth to three months. *Child Development* 51: 295–298.

Hall, J.W. III, and Gross, J.H. 1993. Short-term and long-term effects on the masking level difference following middle ear surgery. *Journal of the American Academy of Audiology* 4:307–12.

Hawley, M.L., Litovsky, R.Y., and Colburn, H.S. 1999. Binaural hearing by listeners with hearing impairments. *Journal of the Acoustical Society of America* 105: 1150.

Litovsky, R. Y. 1997. Developmental changes in the precedence effect: Estimates of minimal audible angle. *Journal of the Acoustical Society of America* 102: 1739–1745.

Litovsky, R. Y., and Ashmead, D. H. 1997. Developmental aspects of binaural and spatial hearing. In R. H. Gilkey, and T. R. Anderson (eds.), *Binaural and spatial hearing in real and virtual environments* (pp. 571–592). Mahwah, NJ: Lawrence Earlbaum Associates.

Litovsky, R.Y., and Clifton, R.K. 1992. Use of sound-pressure level in auditory distance discrimination by 6-month-old infants and adults. *Journal of the Acoustical Society of America* 92: 794–802.

Litovsky, R.Y., Colburn, H.S., Yost, W.A., and Guzman, S. 1999. The precedence effect. Review and Tutorial paper. *Journal of the Acoustical Society of America* 106: 1633–1654.

Litovsky, R.Y., Dalal, A., and Ng, G. 2001. Speech intelligibility and spatial release from masking in young children. *Association for Research in Otolaryngology Abstracts.*

Litovsky, R. Y., and Macmillan, N. A. 1994. Sound localization precision under conditions of the precedence effect: Effects of azimuth and standard stimuli. *Journal of the Acoustical Society of America* 96(2) Pt. 1: 752–758.

Little, A.D., Mershon, D.H., and Cox, P.H. 1992. Spectral content as a cue to perceived auditory distance. *Perception* 21: 405–416.

Makous, J.C., and Middlebrooks, J.C. 1990. Two-dimensional sound localization by human listeners. *Journal of the Acoustical Society of America* 87(5): 2188–2200.

Moore, D.R., Hutchings, M., and Meyer, S. 1991. Binaural masking level differences in children with a history of otitis media. *Audiology* 30: 91–101.

Moore, J.M., Thompson, G., and Thompson, M. 1975. Auditory localization of infants as a function of reinforcement conditions. *Journal of the Acoustical Society of America* 30: 237–246.

Morrongeillo, B. 1988. Infants' localization of sounds along the horizontal axis: Estimates of minimum audible angle. *Developmental Psychology* 24: 8–13.

Morrongeillo, B.A., and Rocca, P.T. 1990. Infants' localization of sounds within hemifields: Estimates of minimum audible angle. *Child Development* 61: 1258–1270.

Muir, W.D., Clifton, R.K., and Clarkson, M.G. 1989. The development of a human auditory localization response: A U-shaped function. *Canadian Journal of Psychology* 43: 199–216.

Muir, D., and Field, J. 1979. Newborn infants orient to sounds. *Child Development* 50: 431–436.

Neuman, A.C., and Hochberg, I. 1983. Children's perception of speech in reverberation. *Journal of the Acoustical Society of America* 73: 2145–2149.

Perris, E.E., and Clifton, R.K. 1988. Reaching in the dark toward sound as a measure of auditory localization in 7-month-old infants. *Infant Behavior and Development* 11: 477–495.

Shaw, B.K., McGowan, R.S., and Turvey, M.T. 1991. An acoustic variable specifying time-to-contact. *Ecological Psychology* 3: 253–261.

Werner, L.A., and Rubel, E.W. 1992. Developmental psychoacoustics. Washington DC: American Psychological Association.

Wightman, F.L., and Kistler, D.J. 1989. Headphone simulation of free-field listening. II: Psychophysical validation. *Journal of the Acoustical Society of America* 85(2): 868–877.

Yonas, A., and Granrud, C. 1985. Reaching as a measure of infants' spatial perception. In G. Gottlieb and N. Krasengor (eds.), *Measurement of audition and vision during the first year of postnatal life: A methodological overview* (pp. 301–322). Norwood, NJ: Ablex.

Yost, W. 1997. The cocktail party problem: Forty years later. In R.H. Gilkey and T.R. Anderson (eds.), *Binaural and spatial hearing* (pp. 329–348). Hillsdale, NJ: Lawrence Earlbaum Associates.

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